In-Situ Observations of Volcanic Plumes for Applications and Research

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aerosonde™

ASTER JAPAN/USA

SCRIPPS INSTITUTION OF OCEANOGRAPHY UCSD

JPL

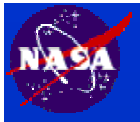
NASA

NATIONAL WEATHER SERVICE

NOAA

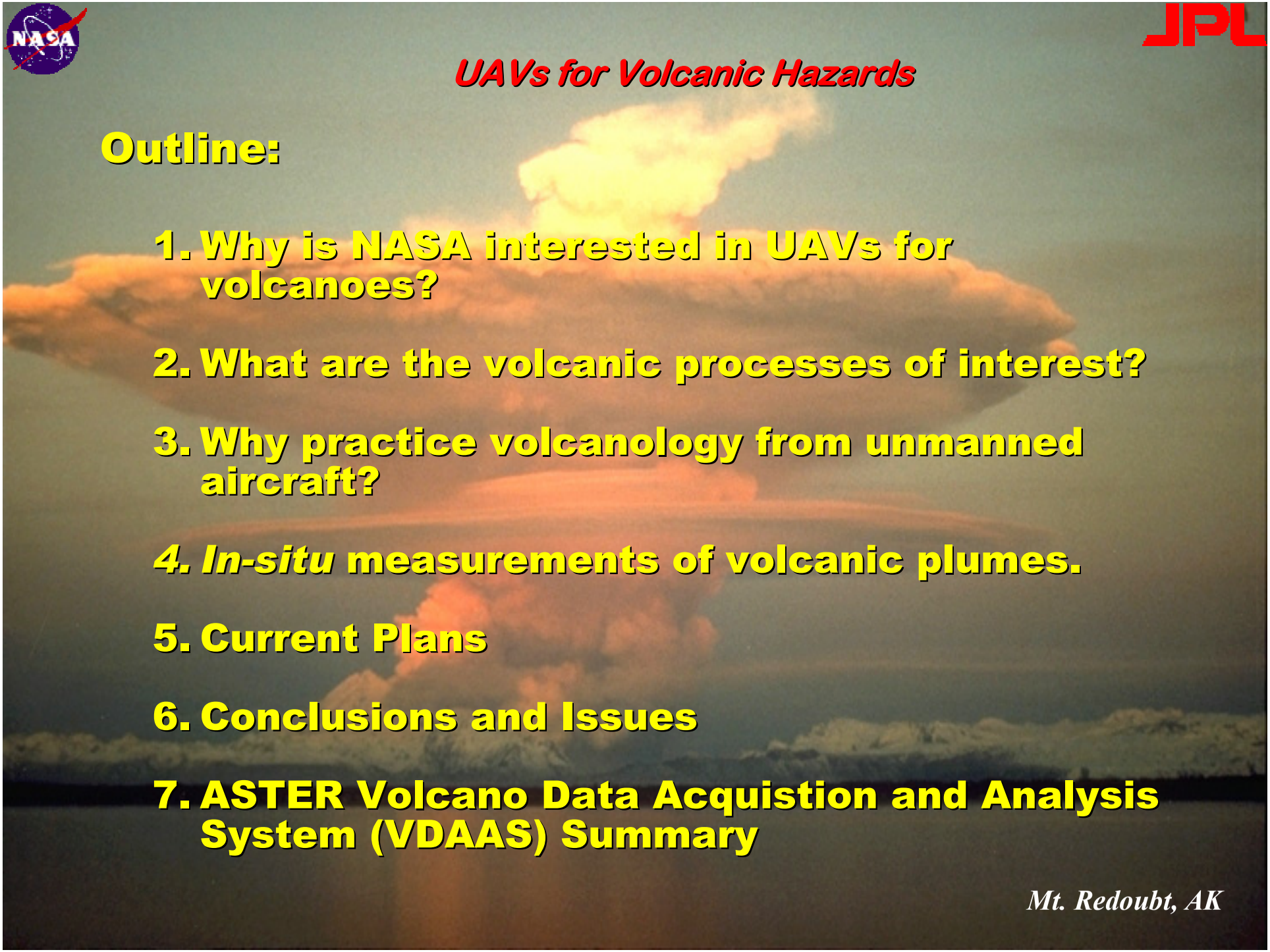
ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Istituto Nazionale di GEOFISICA e VULCANOLOGIA



Collaborators

- **Mike Abrams, JPL, ASTER Science Team Leader**
- **Ali Abtahi, JPL, ASTER Science Team Support**
- **M. Fabrizia Buongiorno, INGV, Remote Sensing Chief, Rome**
- **Greg Holland, Aerosonde North America, NASA Wallops and Melbourne, Australia**
- **Gary Hufford, NWS/NOAA, Alaska Region Chief Scientist**
- **Gian Marco Saggiani, Professor of Aeronautics, University of Bologna**
- **Jim Simpson, Scripps, Dir. Digital Image Analysis Lab**

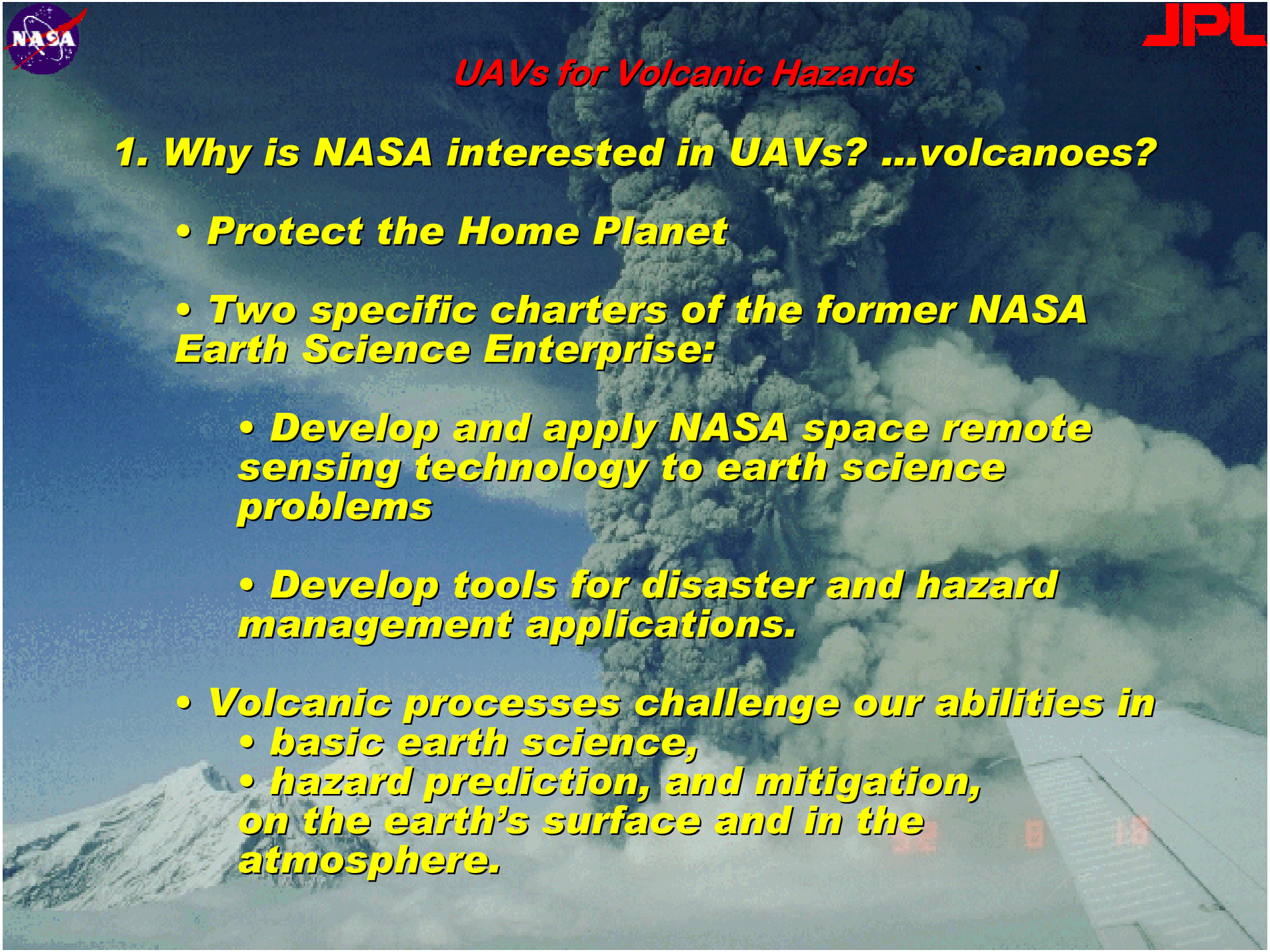


UAVs for Volcanic Hazards

Outline:

1. **Why is NASA interested in UAVs for volcanoes?**
2. **What are the volcanic processes of interest?**
3. **Why practice volcanology from unmanned aircraft?**
4. ***In-situ* measurements of volcanic plumes.**
5. **Current Plans**
6. **Conclusions and Issues**
7. **ASTER Volcano Data Acquistion and Analysis System (VDAAS) Summary**

Mt. Redoubt, AK

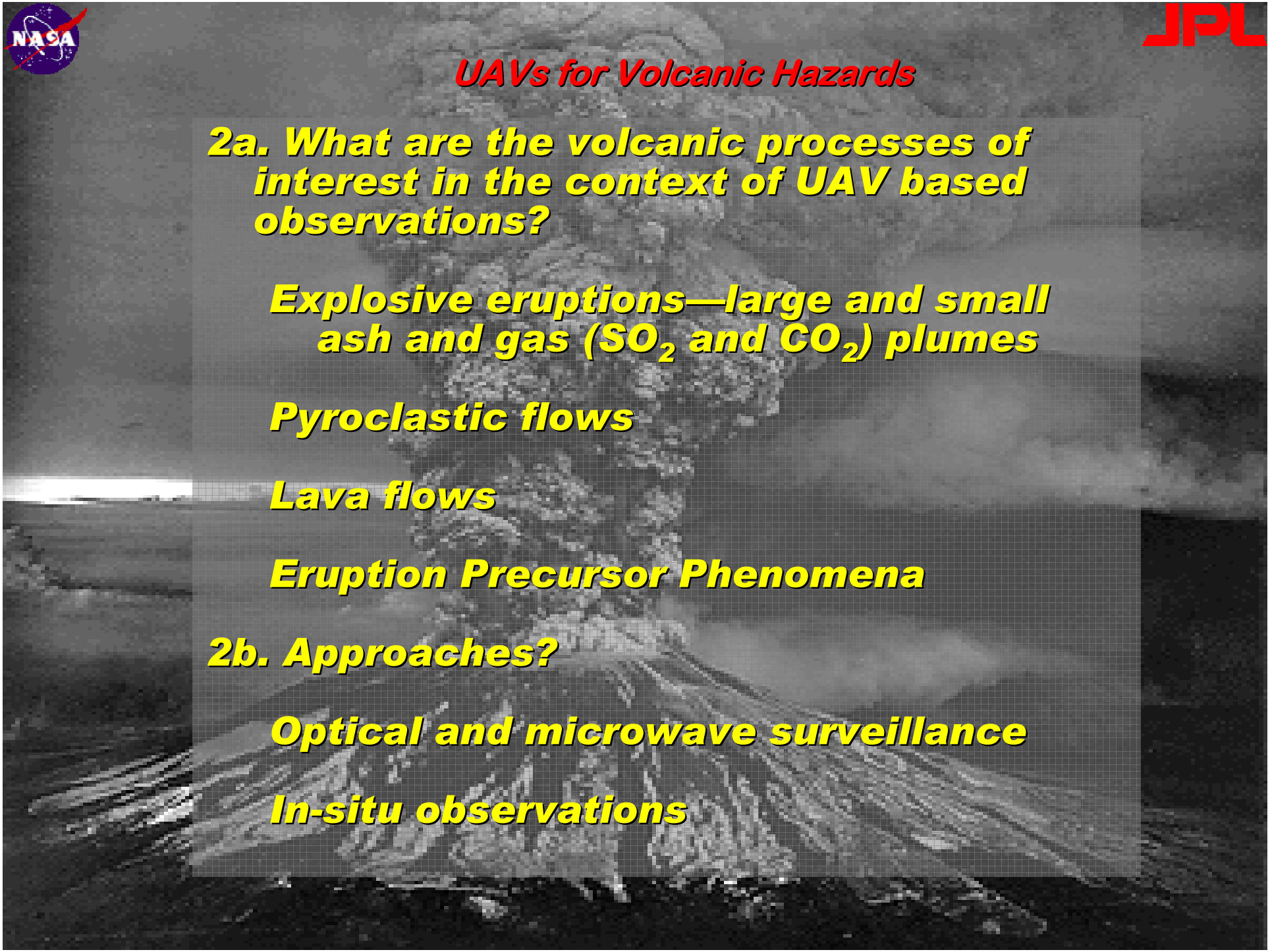


UAVs for Volcanic Hazards

1. Why is NASA interested in UAVs? ...volcanoes?

- Protect the Home Planet
- Two specific charters of the former NASA Earth Science Enterprise:
  - Develop and apply NASA space remote sensing technology to earth science problems
  - Develop tools for disaster and hazard management applications.
- Volcanic processes challenge our abilities in
  - basic earth science,
  - hazard prediction, and mitigation,

  on the earth's surface and in the atmosphere.



UAVs for Volcanic Hazards

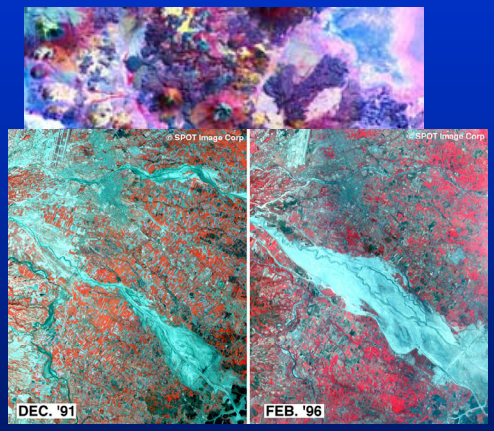
2a. What are the volcanic processes of interest in the context of UAV based observations?

- Explosive eruptions—large and small ash and gas (SO_2 and CO_2) plumes
- Pyroclastic flows
- Lava flows
- Eruption Precursor Phenomena

2b. Approaches?

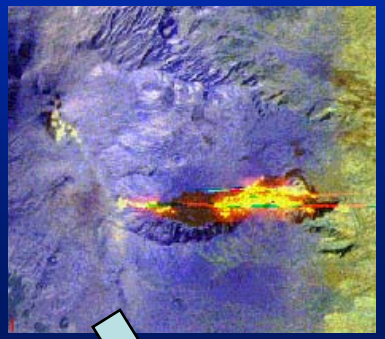
- Optical and microwave surveillance
- In-situ observations

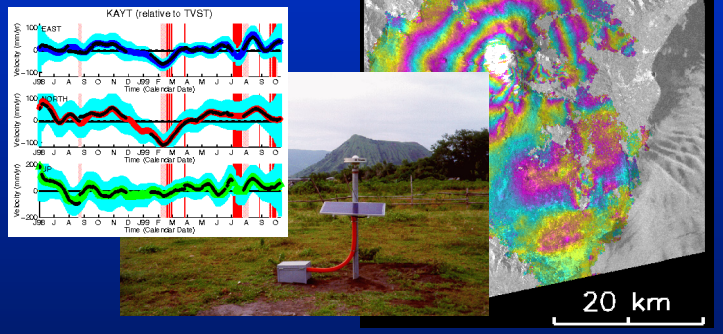
NASA Remote Sensing Volcano Applications



Surface Deposits and Composition

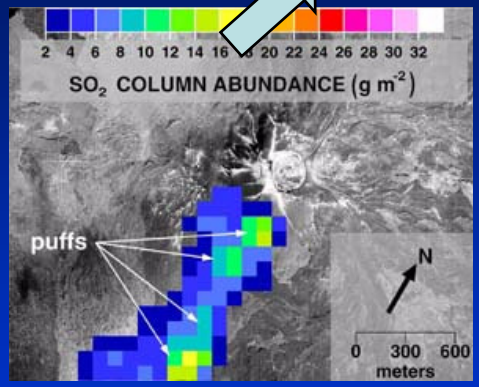
Surface Temperature



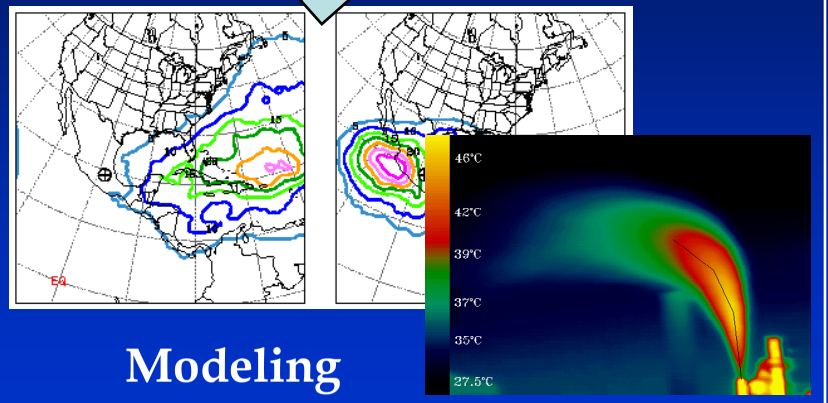


Topography and Surface Deformation

Characterize - Understand - Predict



SO_2 and Ash Detection and Tracking

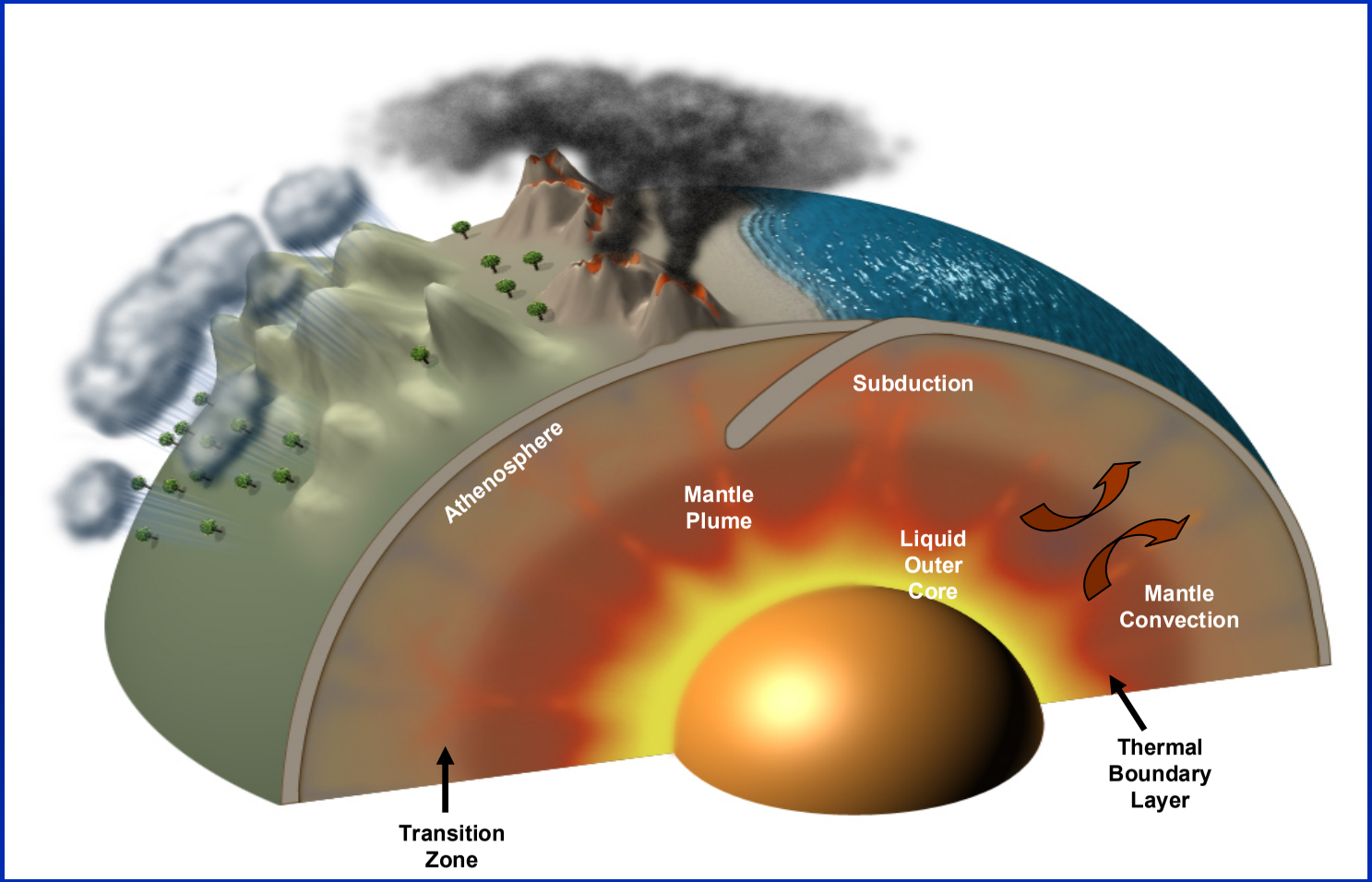


Modeling

VISION:

- 10 years: Long-term record of Surface Strain and emissions
- 20 years: 60-90 day eruption forecasts

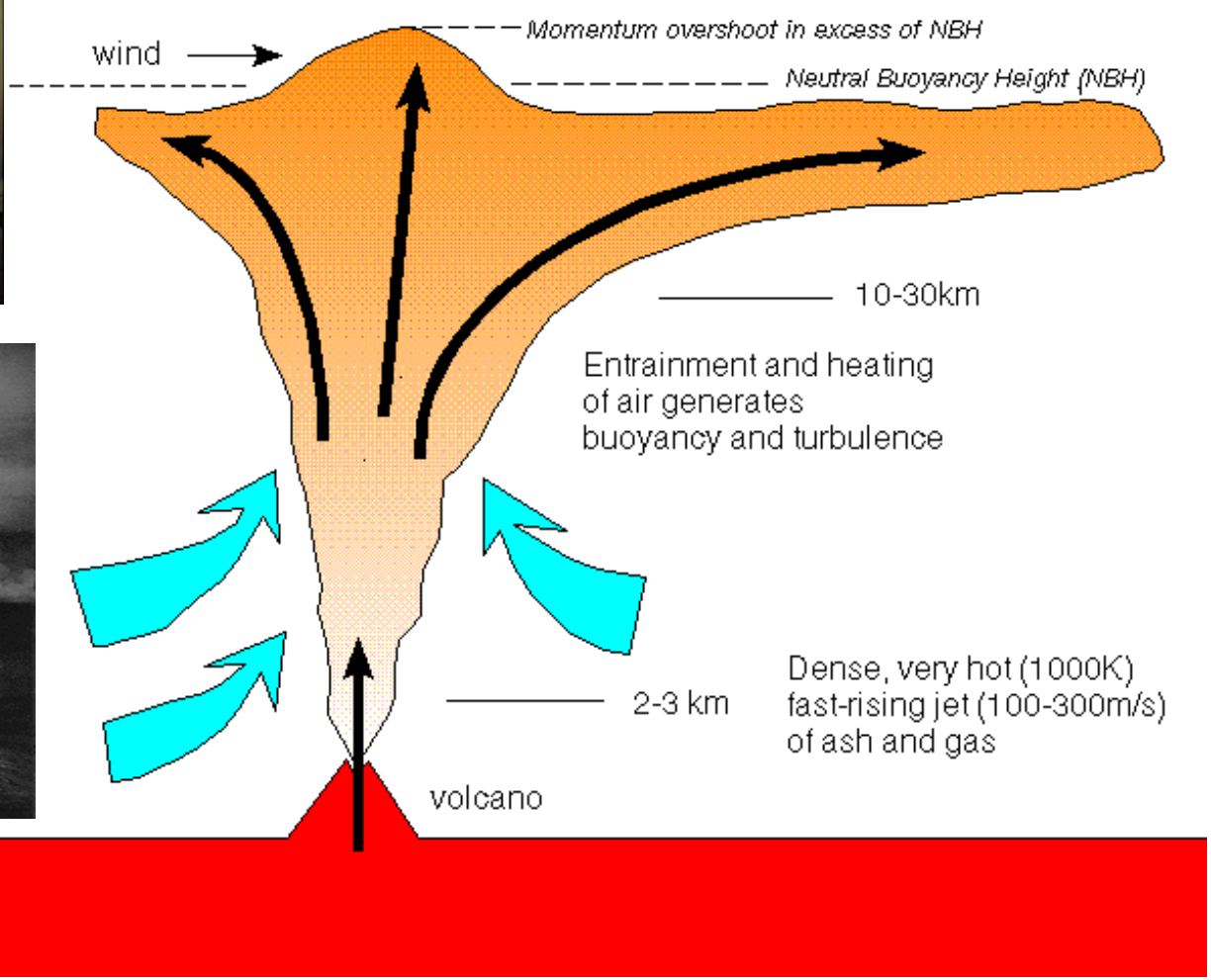
UAVs for Volcanic Hazards

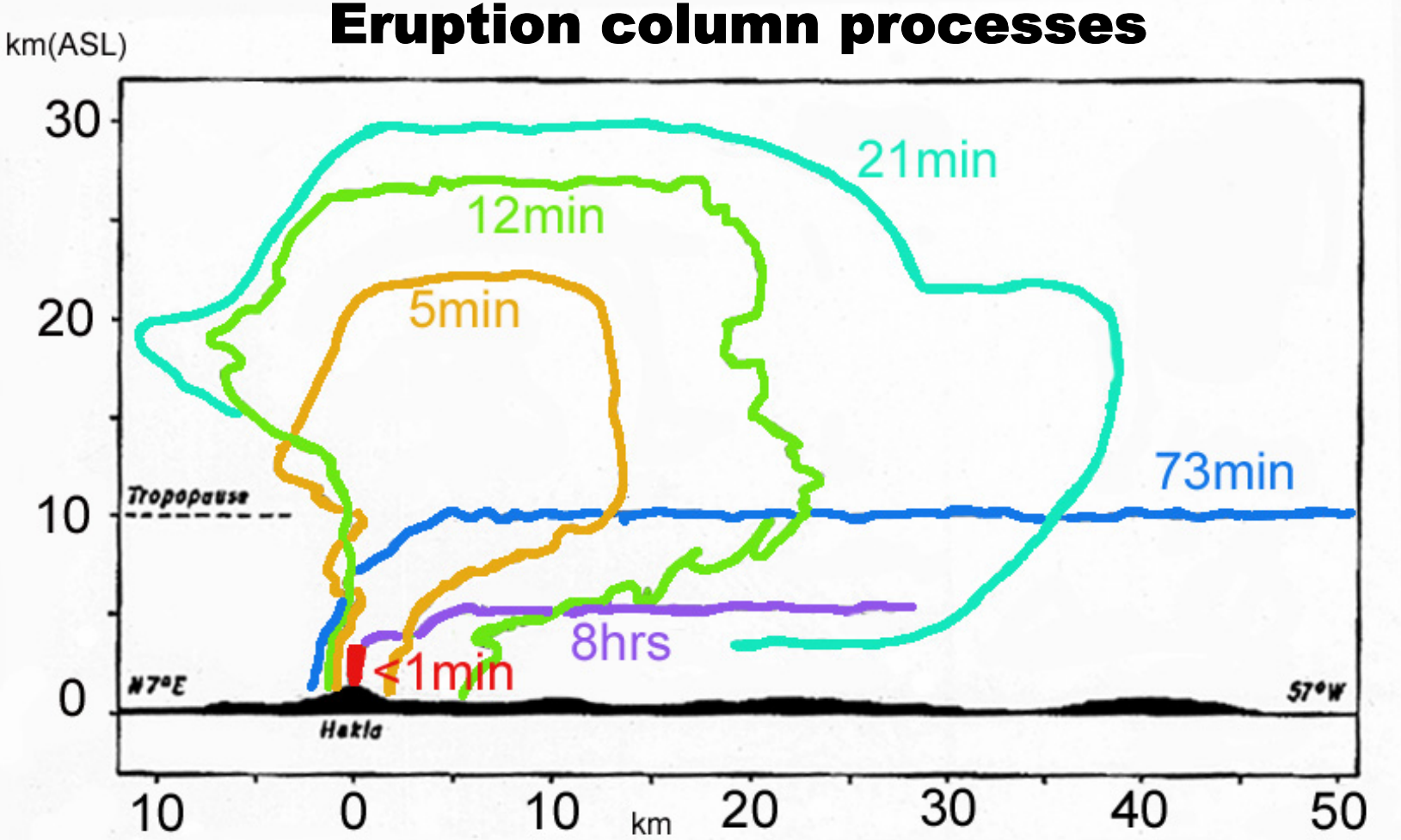


Eruption Processes

UAVs for Volcanic Hazards

Eruption column processes

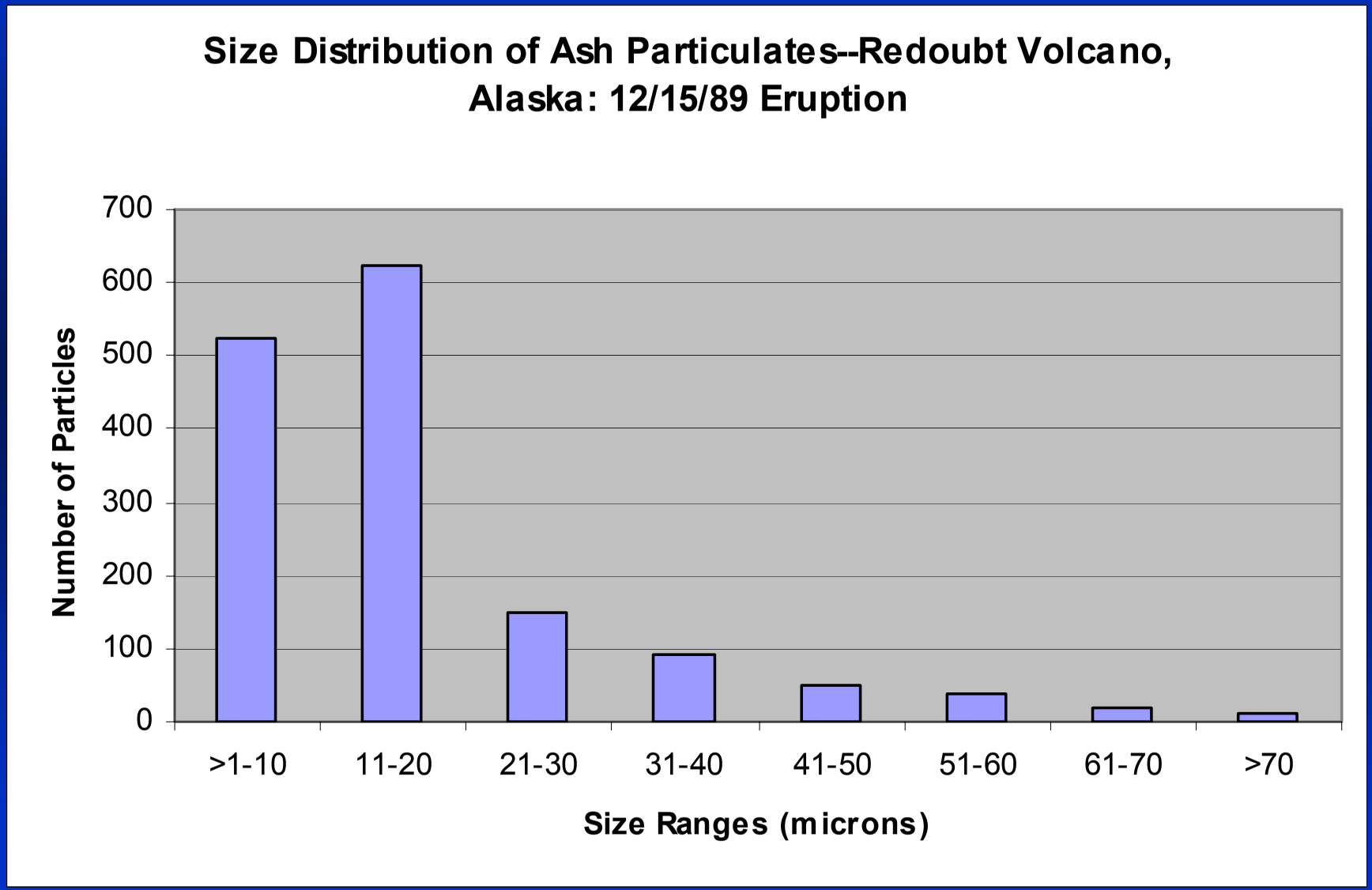


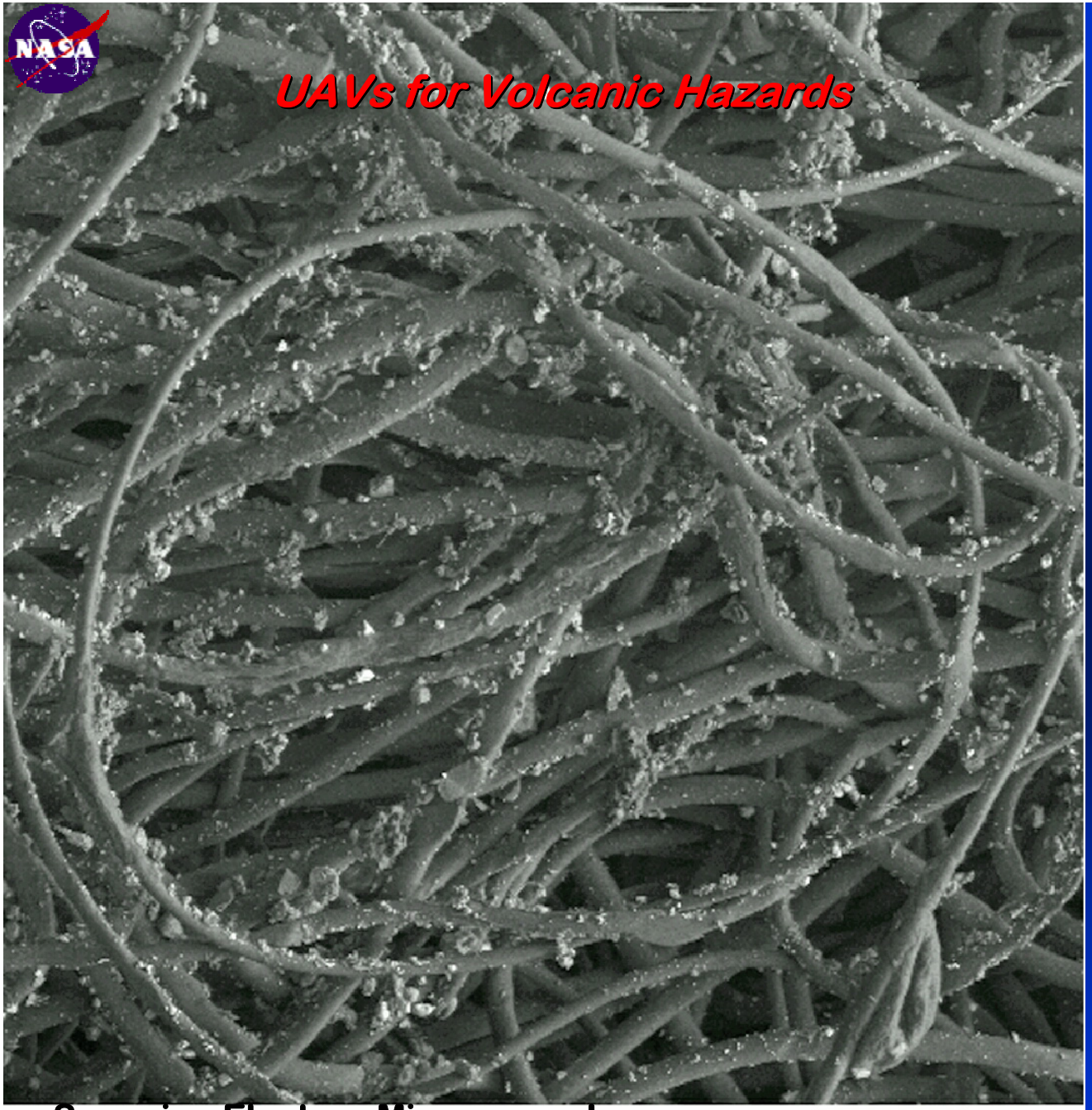


Growth of the 1947 Hekla Plume

(after Thorarinsson, 1954)

Fragmentation of Basalt





Scanning Electron Microscope Image

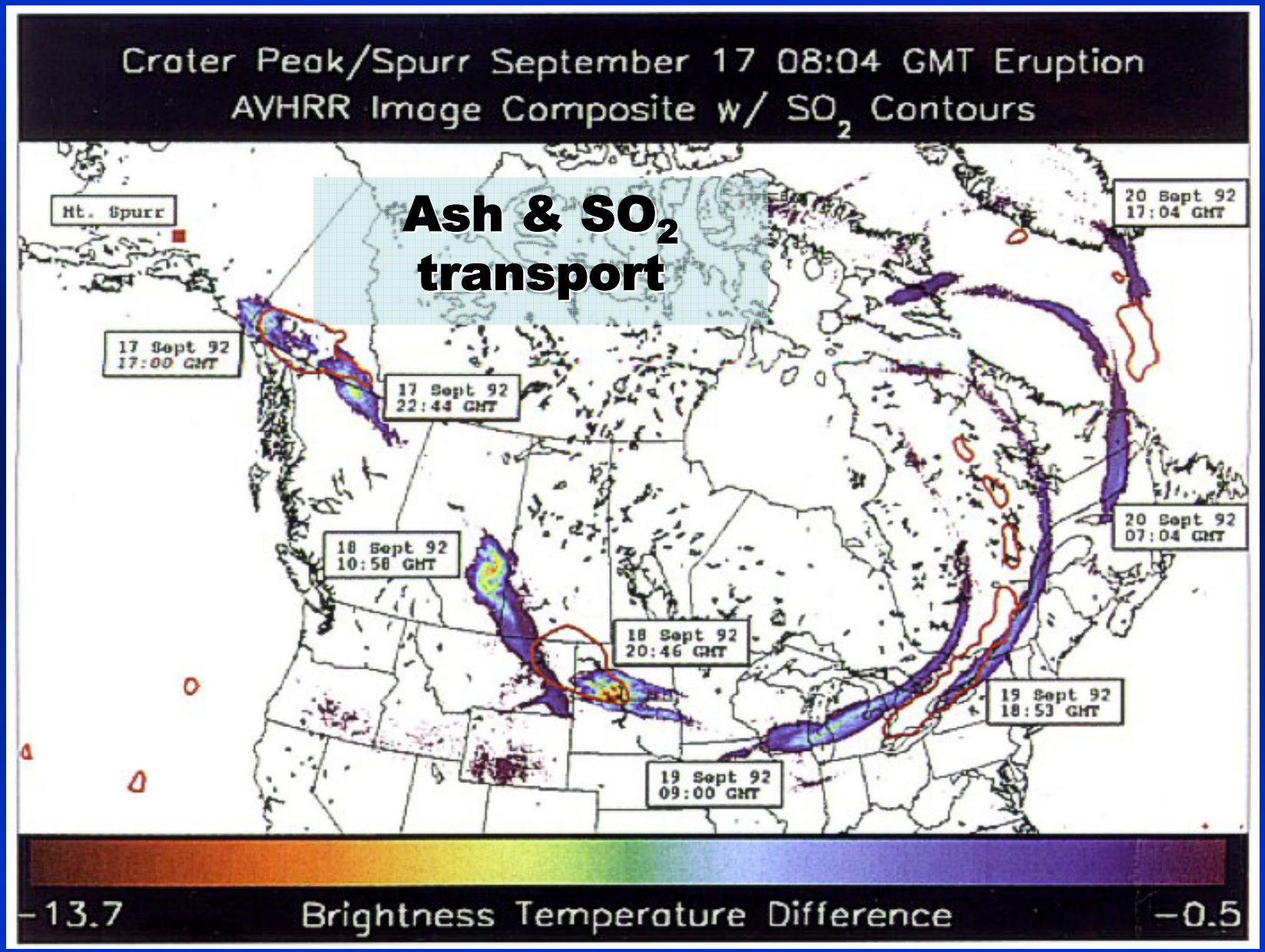
From Pieri et al., 2002, GRL

Fragmentation of basalt

Hekla 2000 eruption—ash recovered from NASA DC-8 air filter

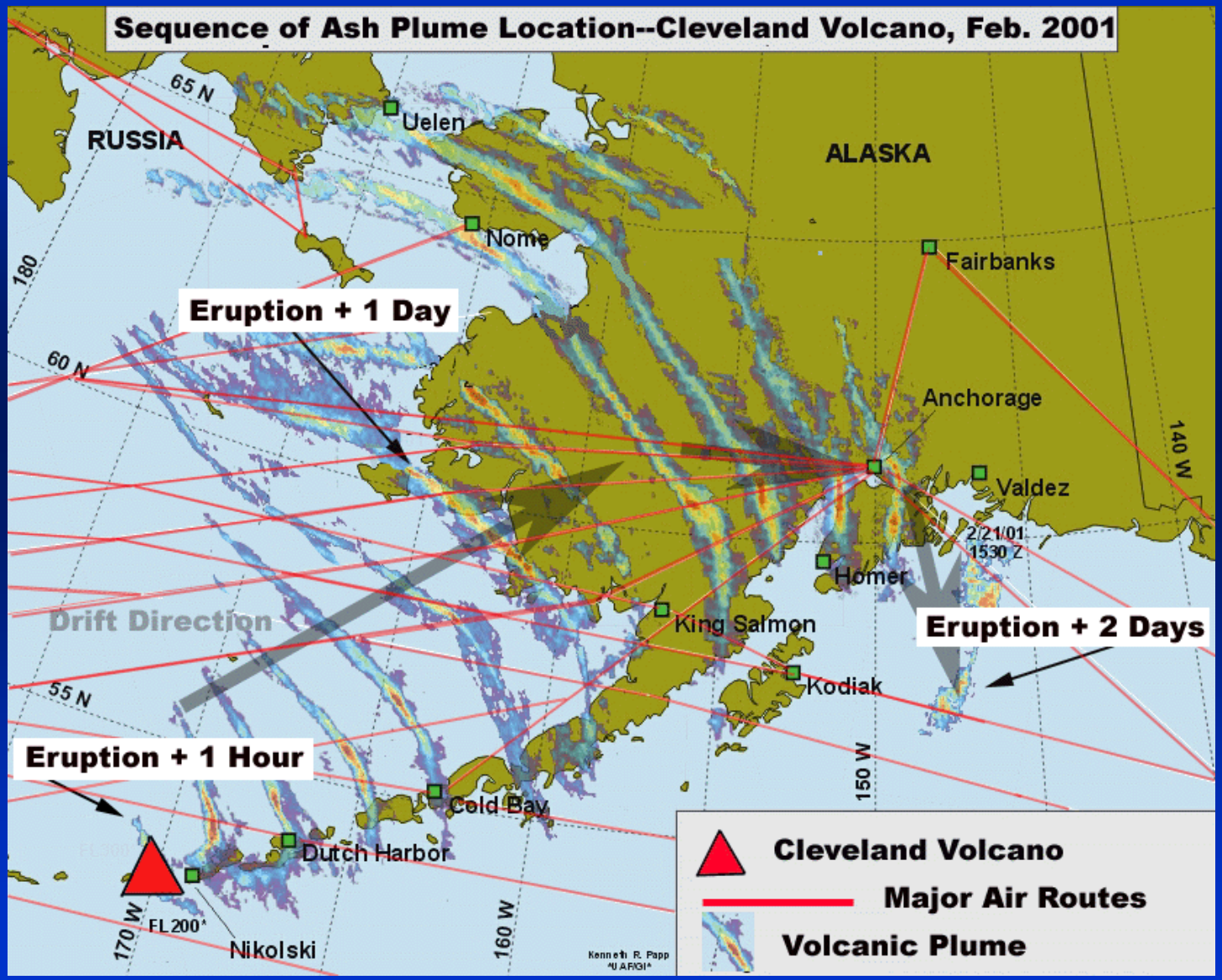
~$3-4M engine damage

UAVs for Volcanic Hazards


Crater Peak/Spurr September 17 08:04 GMT Eruption
AVHRR Image Composite w/ SO_2 Contours
Ash & SO_2 transport
Mt. Spurr
17 Sept 92 17:00 GMT
17 Sept 92 22:44 GMT
18 Sept 92 10:58 GMT
18 Sept 92 20:46 GMT
19 Sept 92 09:00 GMT
19 Sept 92 18:53 GMT
20 Sept 92 07:04 GMT
20 Sept 92 17:04 GMT
-13.7
Brightness Temperature Difference
-0.5

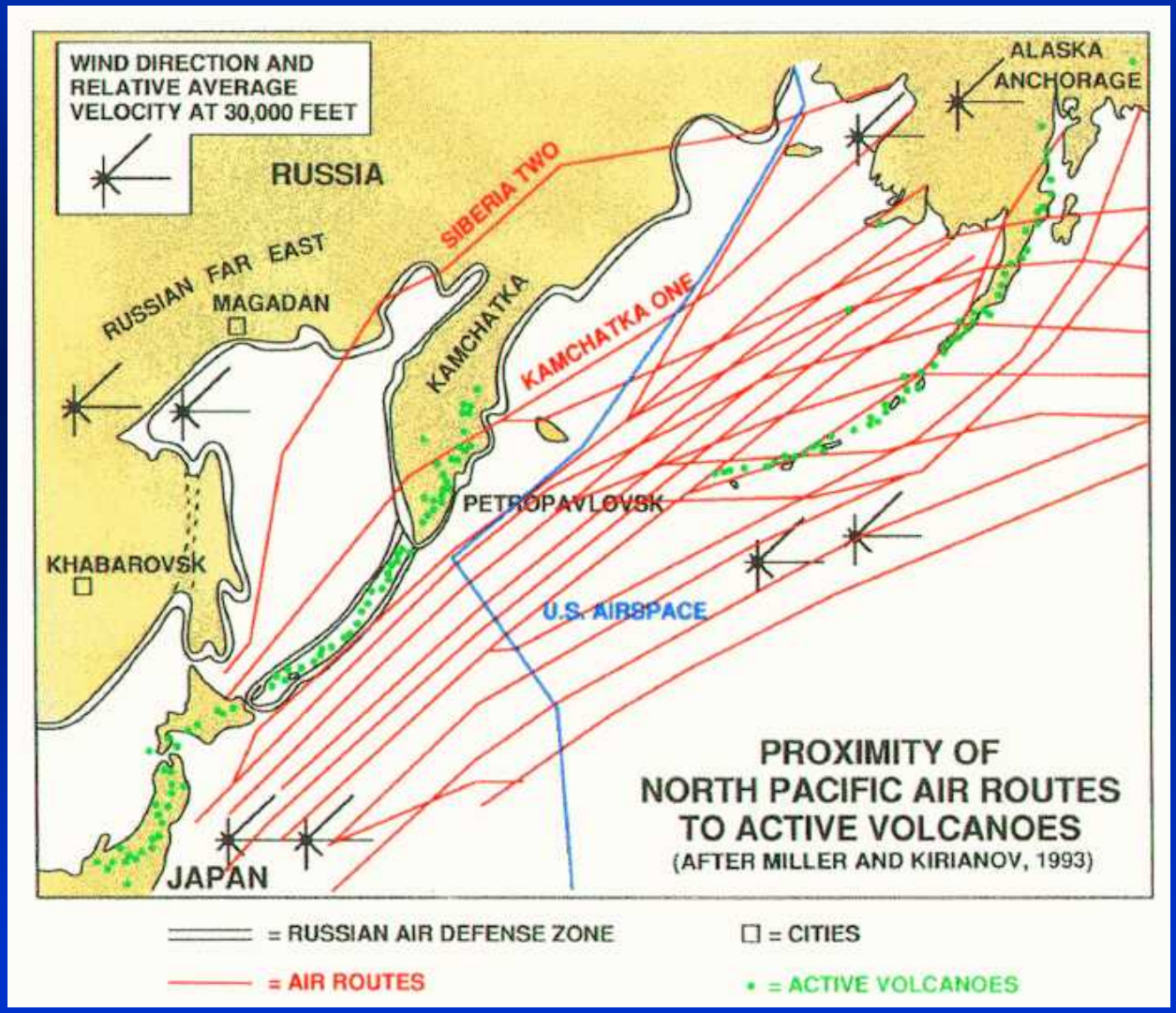
UAVs for Volcanic Hazards

The threat to aviation—Distal Hazards



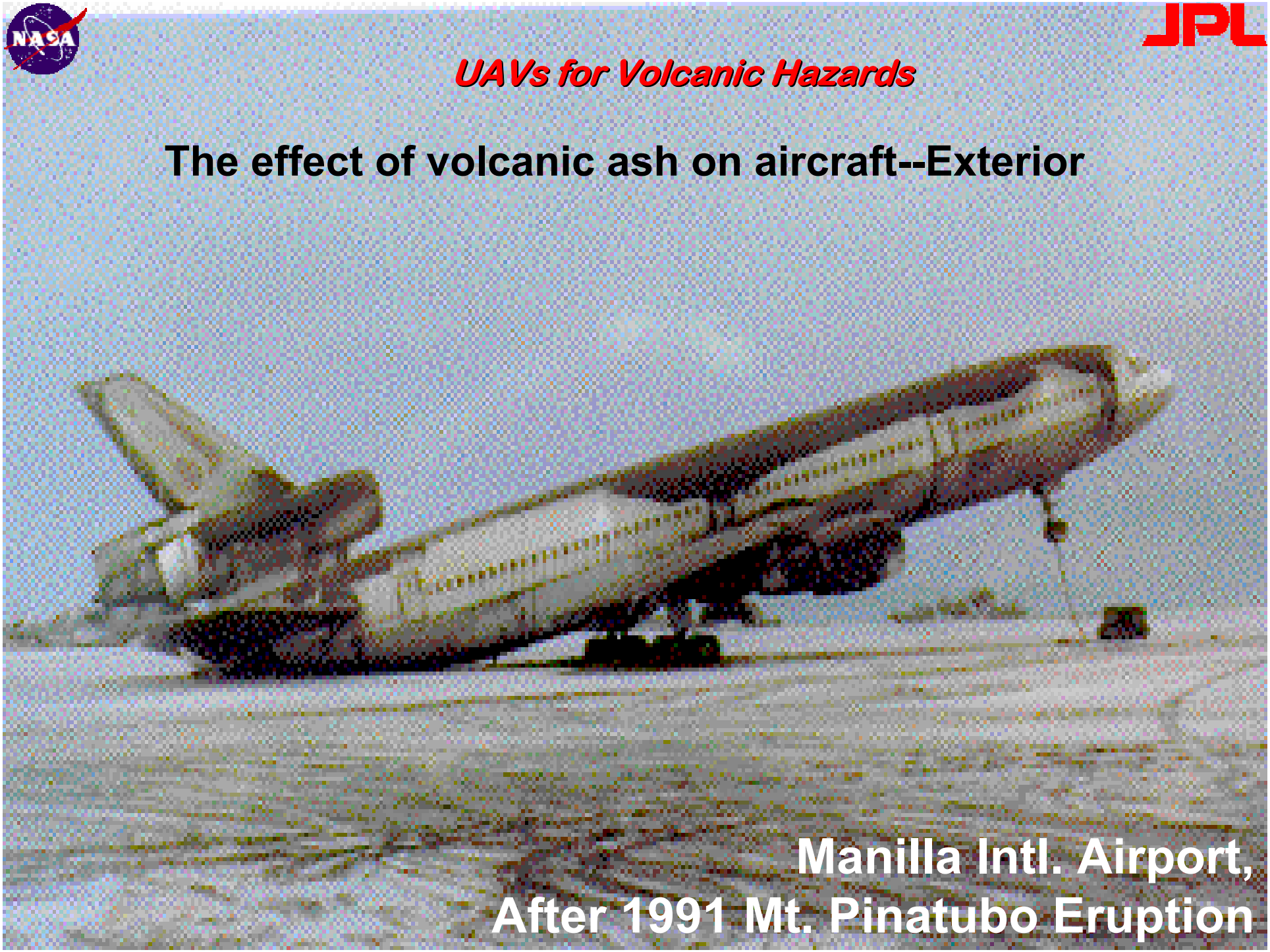
UAVs for Volcanic Hazards

The threat to aviation—Distal Hazards



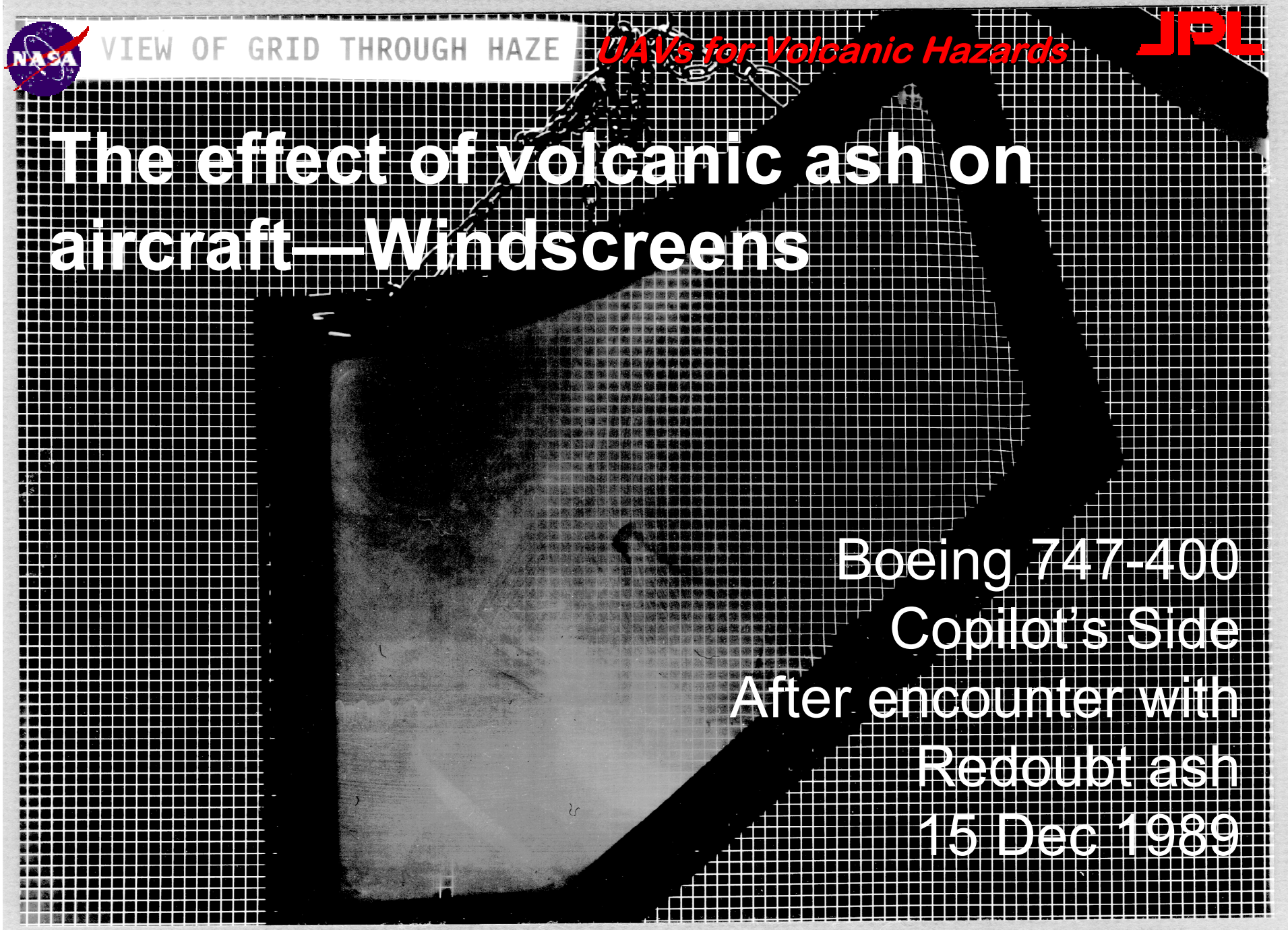
UAVs for Volcanic Hazards
The threat to aviation—
Proximal Hazards
Hand held
Photo from
Space Shuttle
22 July 2000
Catania International Airport
Sigonella U.S. Naval Air Station

The effect of volcanic ash on aircraft--Exterior

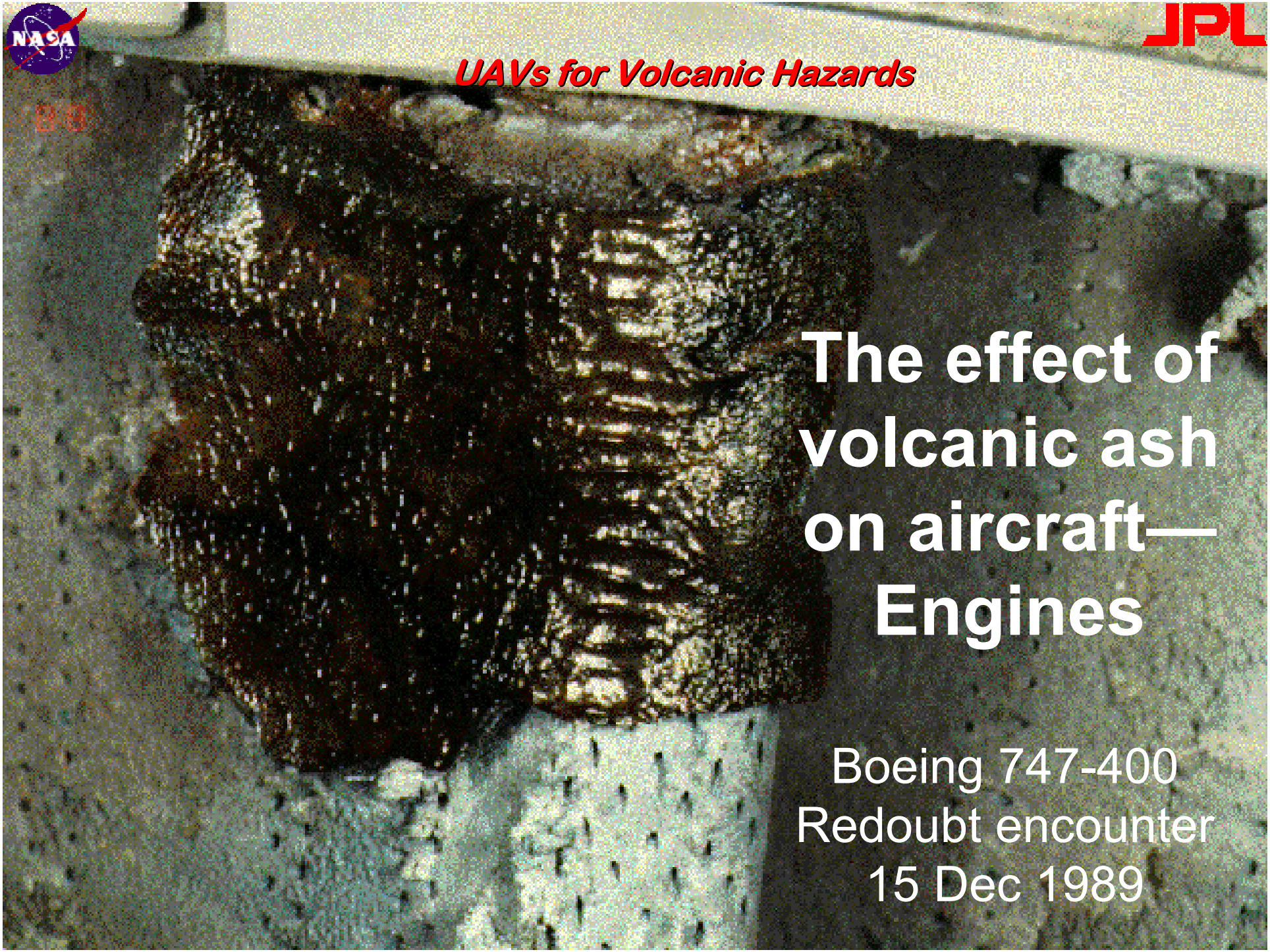


Manilla Intl. Airport,
After 1991 Mt. Pinatubo Eruption

The effect of volcanic ash on aircraft—Windscreens

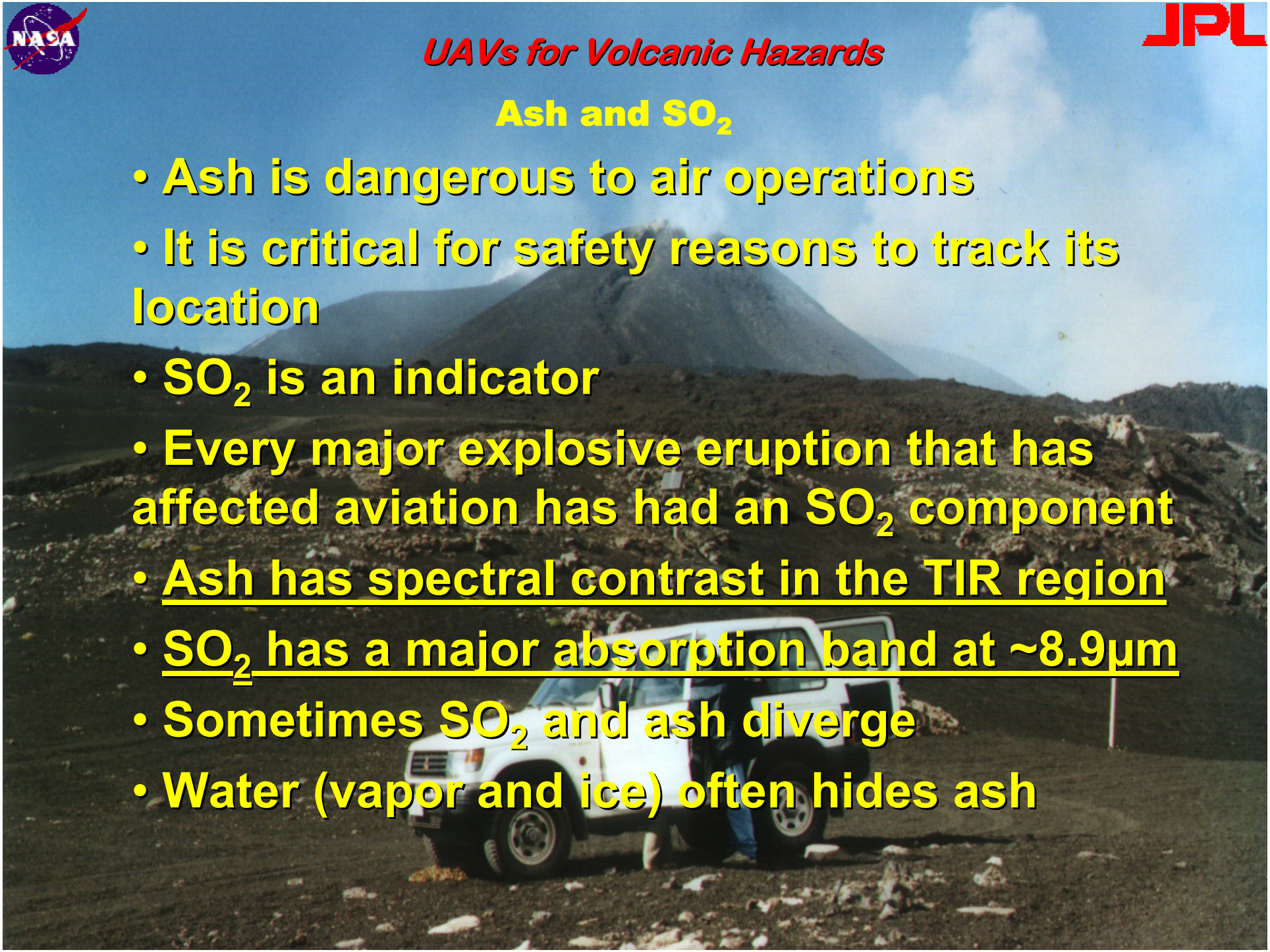


Boeing 747-400
Copilot's Side
After encounter with
Redoubt ash
15 Dec 1989



The effect of volcanic ash on aircraft—Engines

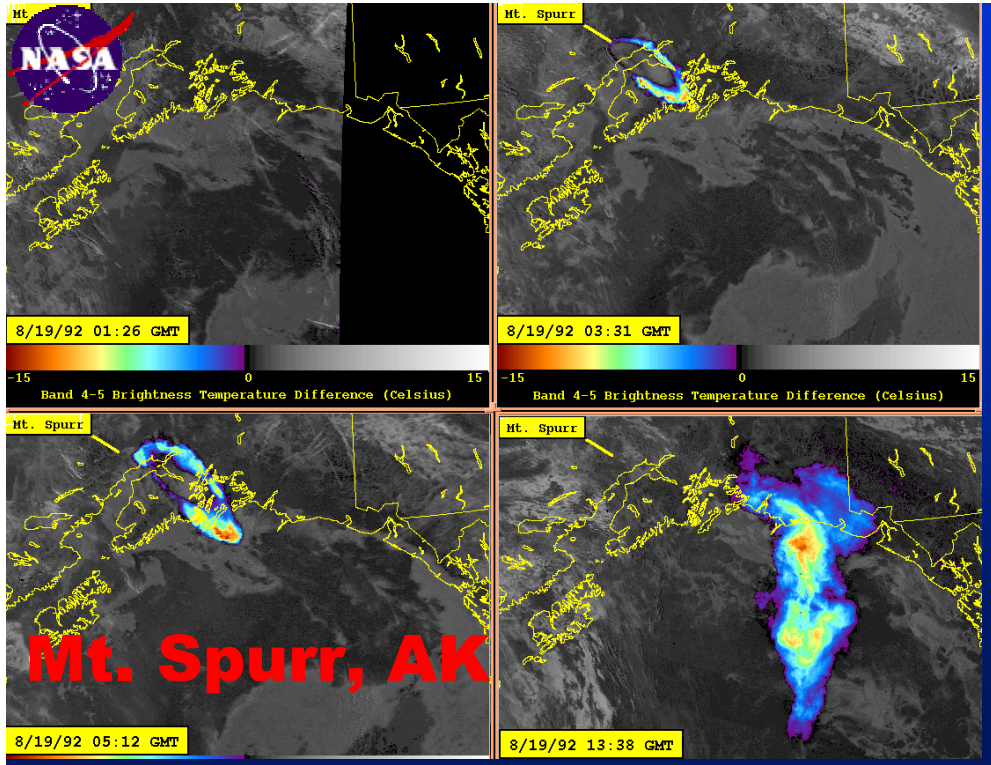
Boeing 747-400
Redoubt encounter
15 Dec 1989



UAVs for Volcanic Hazards

Ash and SO_2

- Ash is dangerous to air operations
- It is critical for safety reasons to track its location
- SO_2 is an indicator
- Every major explosive eruption that has affected aviation has had an SO_2 component
- Ash has spectral contrast in the TIR region
- SO_2 has a major absorption band at ~8.9µm
- Sometimes SO_2 and ash diverge
- Water (vapor and ice) often hides ash



UAVs for Volcanic Hazards

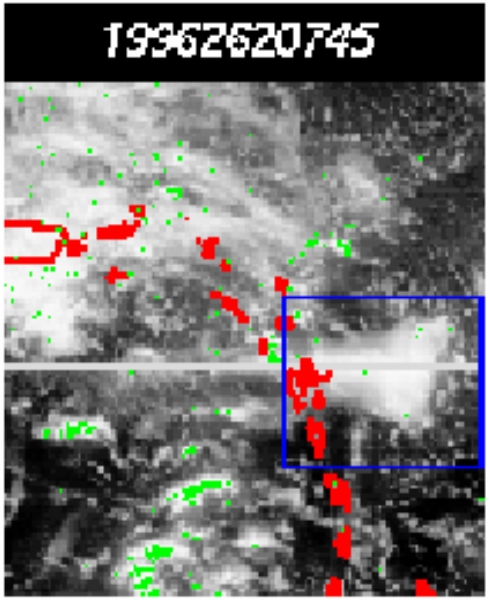
Seeing Ash with TIR Split Window

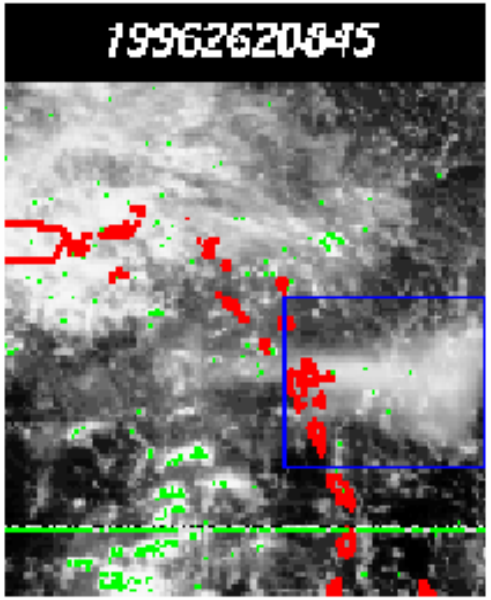
Comparison of Mt. Spurr '92 (polar dry) plume detection with La Soufriere (Montserrat) '96 (tropical wet) –

"Band 4 (10μm) minus 5 (12 μm)subtraction technique" or "split window technique."

- **Split Window technique only works after plume has become translucent to upwelling TIR radiation.**
- **Water vapor is confounding.**
- **Use of shorter TIR bands (e.g., 7-9 μm) could improve things.**

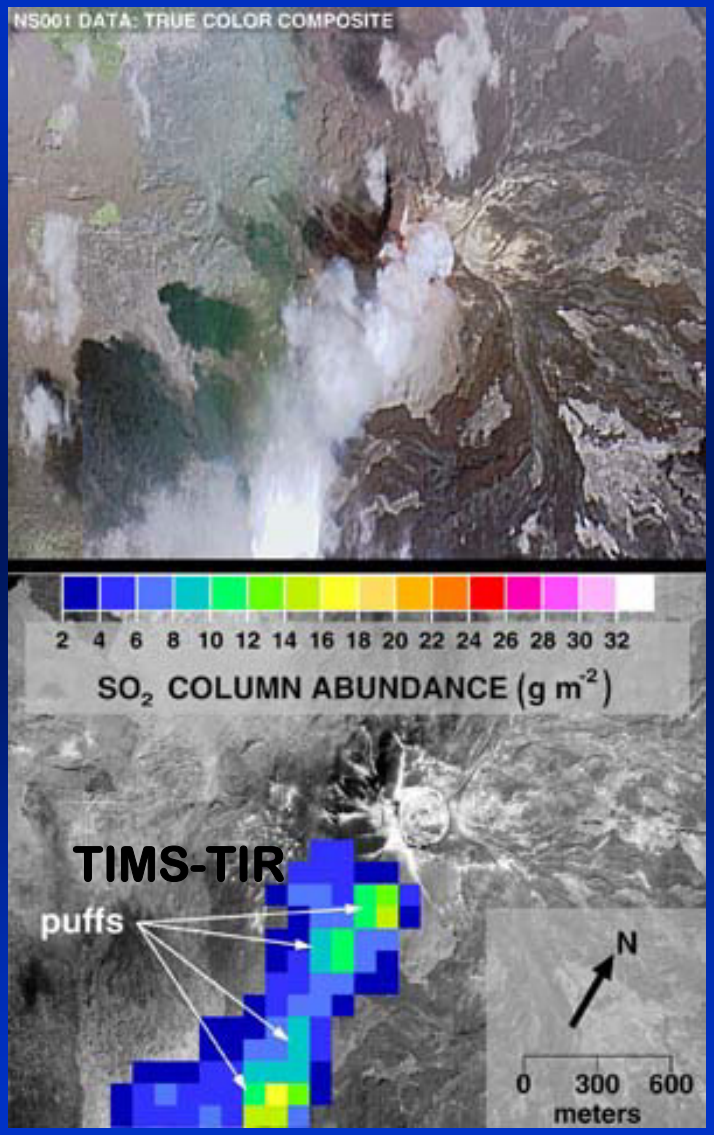
Montserrat, West Indies



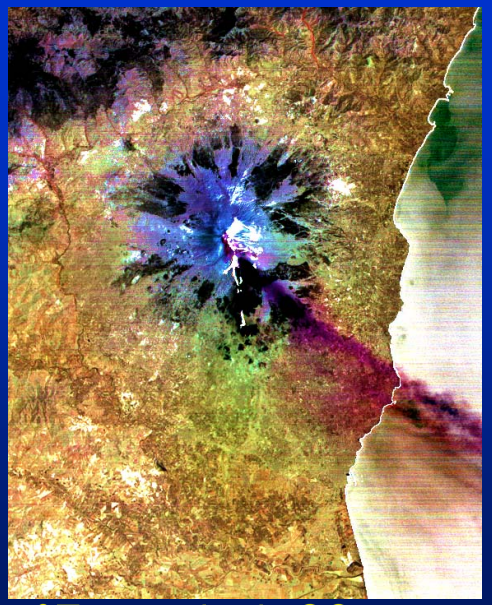


UAVs for Volcanic Hazards

SO_2 Detection and Tracking

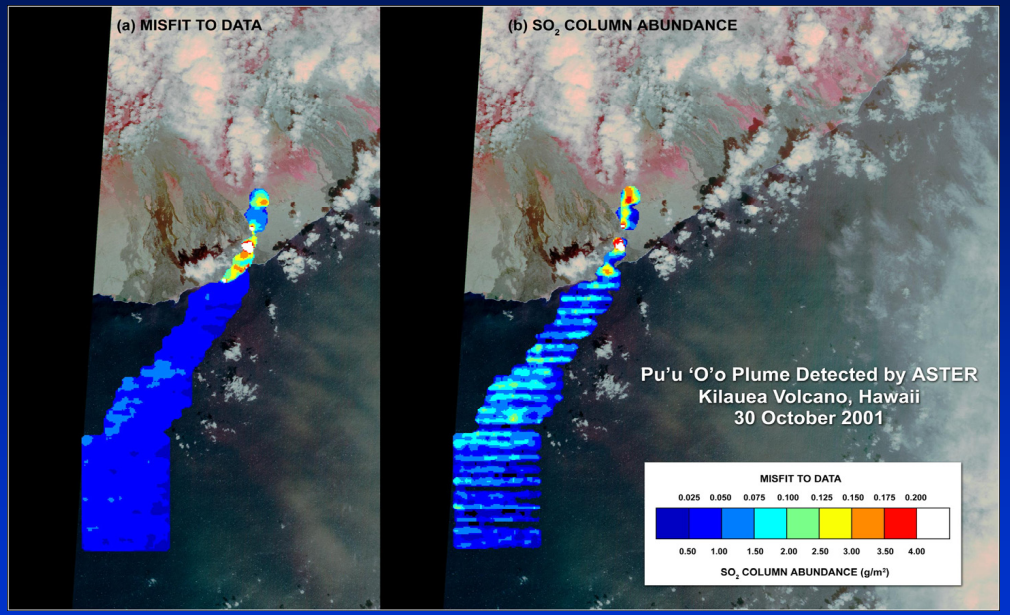

NS001 DATA: TRUE COLOR COMPOSITE
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
SO2 COLUMN ABUNDANCE (g m-2)
TIMS-TIR
puffs
N
0 300 600
meters

Courtesy Vince Realmuto, JPL



Airborne Detection from NASA C130 in over PuuOo Vent, Kilauea (left)

Orbital Detection of Tropospheric SO_2
ASTER over Hawaii (below) and Mt. Etna, Italy (above)


(a) MISFIT TO DATA
(b) SO2 COLUMN ABUNDANCE
Pu'u 'O'o Plume Detected by ASTER
Kilauea Volcano, Hawaii
30 October 2001
MISFIT TO DATA
0.025 0.050 0.075 0.100 0.125 0.150 0.175 0.200
0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00
SO2 COLUMN ABUNDANCE (g/m2)

3. Why practice volcanology from unmanned aircraft?

UAVs:

- **Reduce human risk.**

- **Can provide *in-situ* observations of volcanic eruption phenomena in Hazardous Flight Environments (HFEs).**

- **May be deployed promptly;**
  (including prompt monitoring of volcanic plumes, lava flows, debris flows and summit crater activity).

3. Why practice volcanology from unmanned aircraft? (continued)

UAVs:

- Can operate for long durations if need be; as well as economical long-duration or periodic surveillance of eruption precursors.

- Can provide on-demand cal/val support for orbital observations of transient phenomena under difficult conditions.

- Such observations also provide critical calibration and validation support for observations from orbital platforms.

- Can reduce cost--Capital investment can be low for small UAVs but deployment costs can be daunting for scientific investigations.

4. Activities:

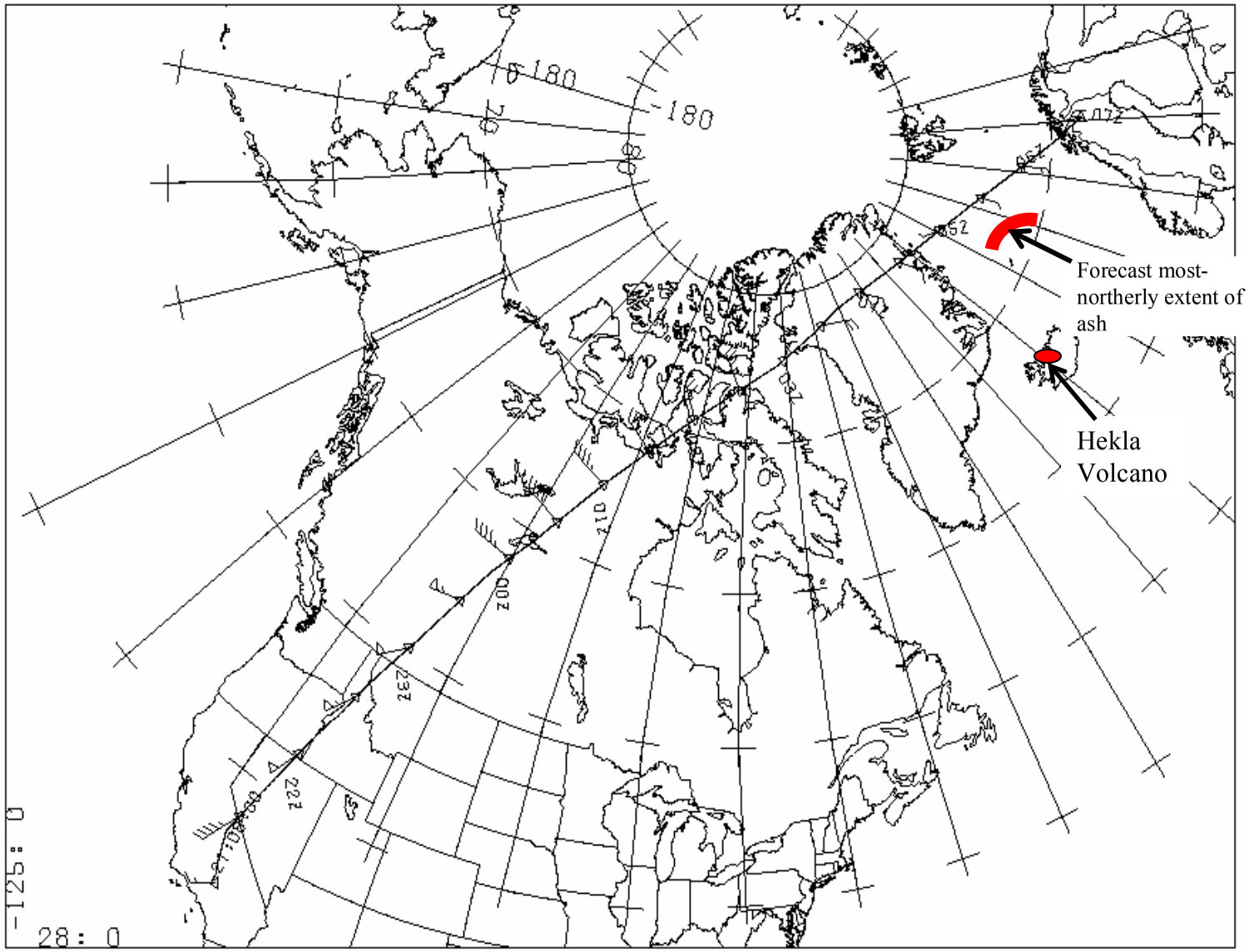
In-situ measurements of volcanic plumes

- Single year of Code YO funding
- Analyses of NASA DC-8 Hekla encounter particulates (Pieri *et al.*, *GRL*)—established the presence of volcanic ash (with Code YS).
- Development and test activities with Aerosonde and UniBo UAVs to sample gas (e.g., SO_2) and solid aerosols (e.g., silicate ash) for drifting volcanic eruption clouds.
- Development of 2nd generation SO2 sensor.
- Calibration and validation of ASTER SO_2 and ash observations (in progress).
- Pending UAV volcanological deployments plans for FY05—Hawaii at Kilauea (PuOo) and Stromboli Volcano in Italy.

***In-situ* measurements of a volcanic plume with the NASA DC-8 (not a UAV)**

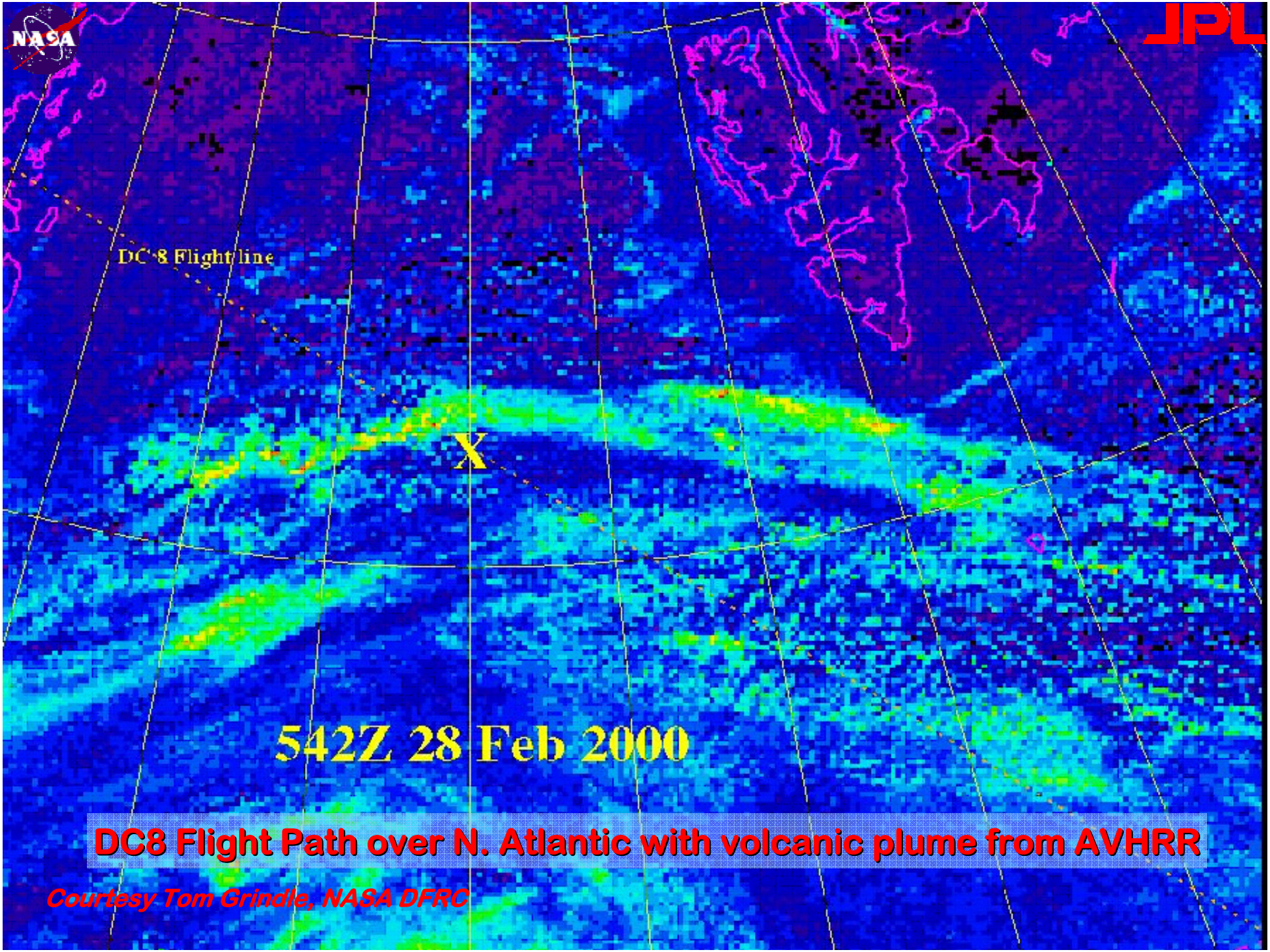
The NASA DC-8 encounter with Hekla Ash

- NASA DC8-72 was en-route Edwards AFB/NASA Dryden FRC to Kiruna, Sweden departing on 27 Feb 2000
- Hekla erupted on 26 Feb with plume ht of 45KftASL
- Ground track of NASA a/c adjusted 200 nautical miles north for safety
- 0527Z on 28 Feb elevated SO_2 readings were noticed onboard
- No St. Elmo's Fire, no windscreen abrasion, no change in engine instruments
- Stars were not visible during the encounter, but were visible 7 minutes later, after the encounter, coincident with drop in SO_2
- At Kiruna, engine air conditioning filters were replaced, oil was changed, no borescope available
- 68 flight hours later at Edwards, borescoping reveals engine damage
- $3.2M repair bill for all four CFM56-2s got NASA's attention


Forecast most-northerly extent of ash
Hekla Volcano
-125: 0
28: 0
SOLVE FLT 000123 FEBRUARY 27, 2000 DRYDEN - KIRUNA
DC8←DATA.FLT
21:07:50 TO 7:11:00 UT SCALE 1:4.30E+07 TIME TIC EVERY 30.00 MINUTES

Ground track of NASA DC-8 volcanic ash encounter, flight 123, Feb 27-28, 2000, Edwards, USA to Kiruna Sweden

Courtesy Tom Grindle, NASA DFRC

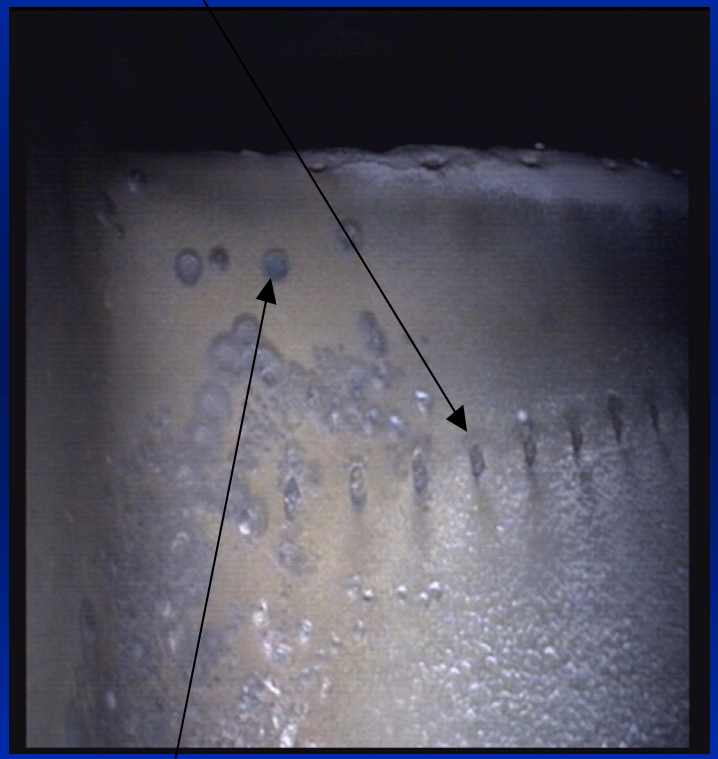


DC8 Flight Path over N. Atlantic with volcanic plume from AVHRR

Courtesy Tom Grindle, NASA DFRC

DC8 Engine Internal Damage

Plugged Cooling Holes



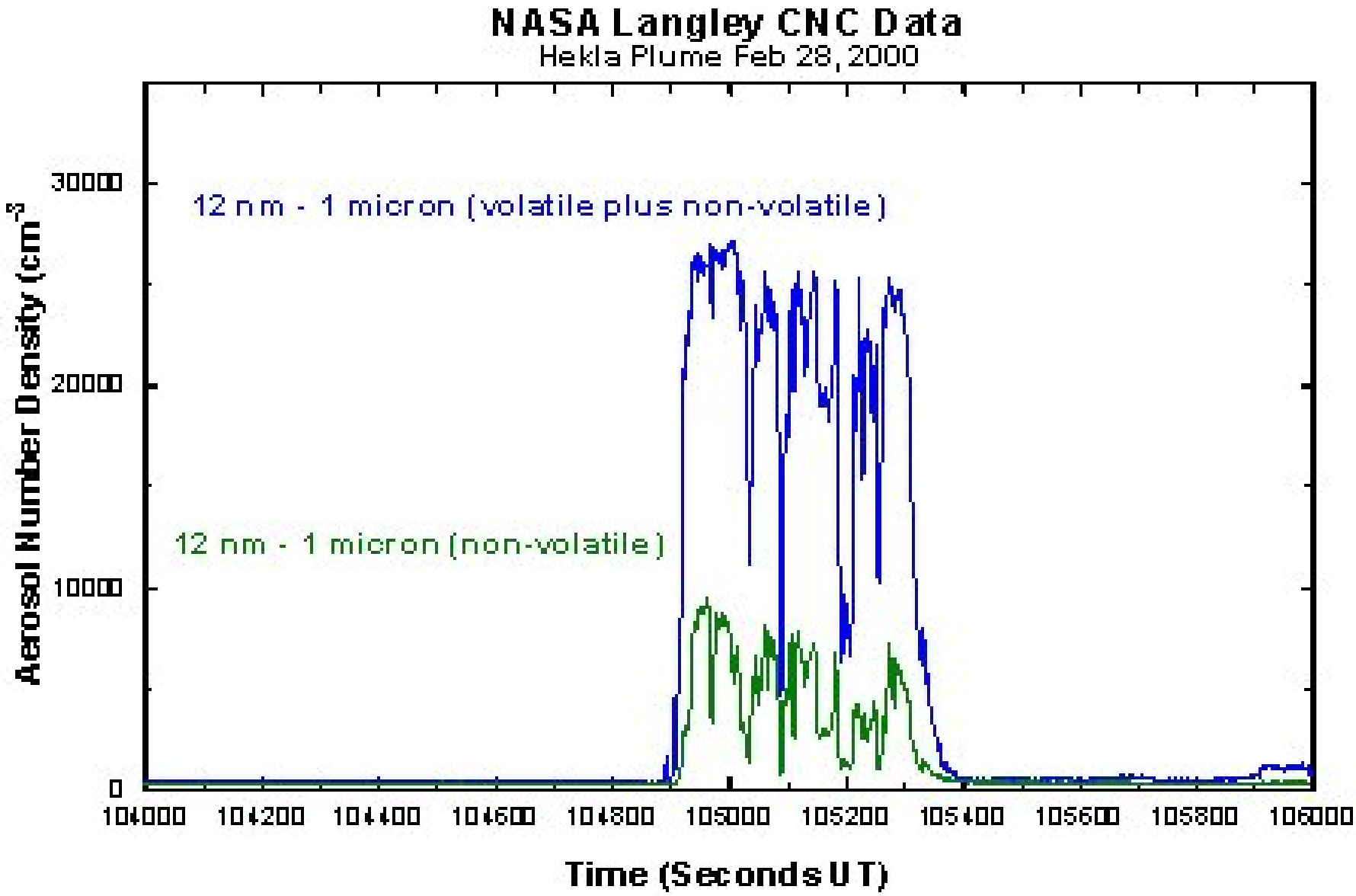
Blistered thermal coating

Erosion of Leading Edge

Build-up of Ash
Inside Passages

Courtesy Tom Grindle, NASA DFRC

Heated DC8 On-Board Particle Detector



Courtesy Tom Grindle, NASA DFRC

Scanning Electron Microscope Images of DC-9 Air Conditioning Filter

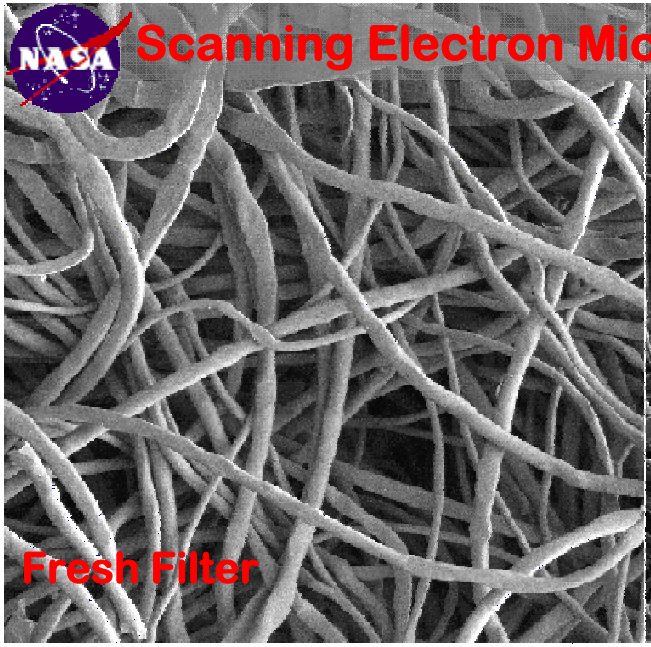


Figure 1a. 100µm 150X

Figure 1b. 100µm 150X

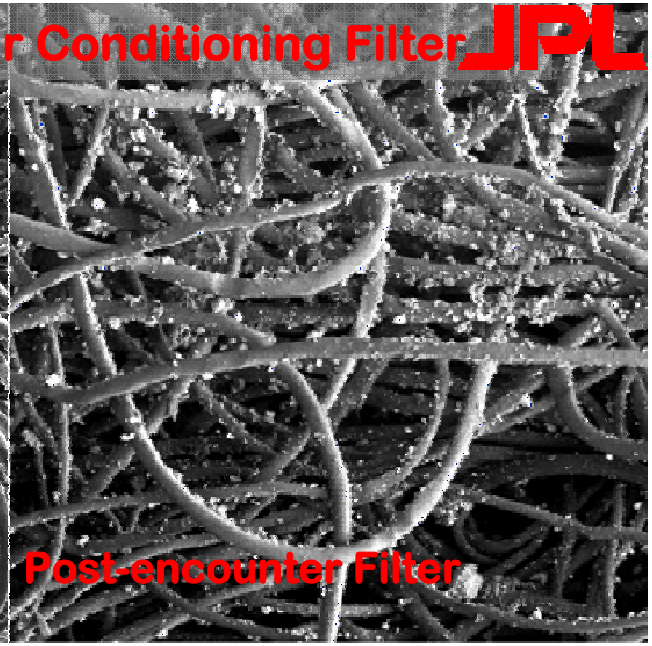


Figure 1c. 100µm 150X

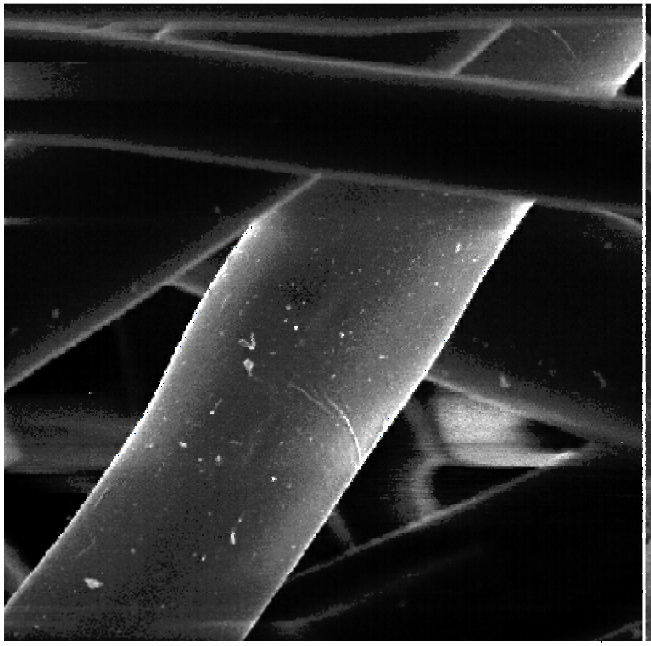


Figure 1d. 10µm 2000X

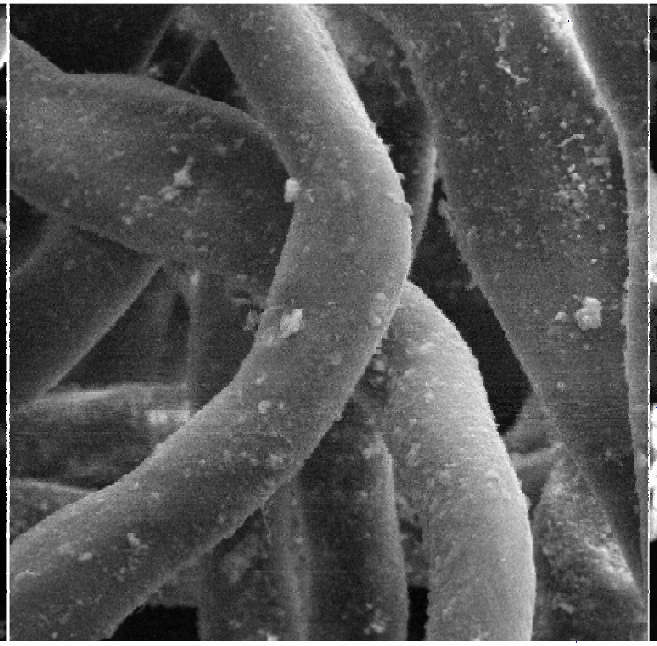


Figure 1e. 10µm 1500X

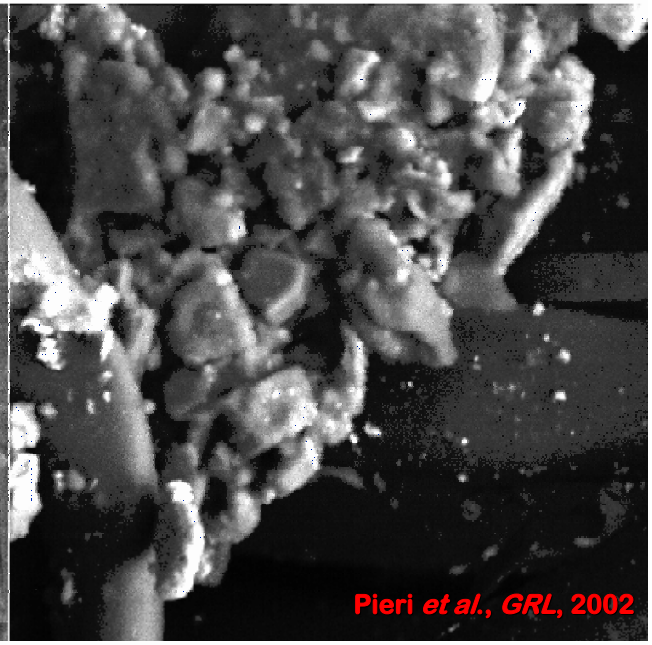


Figure 1f. 10µm 1500X

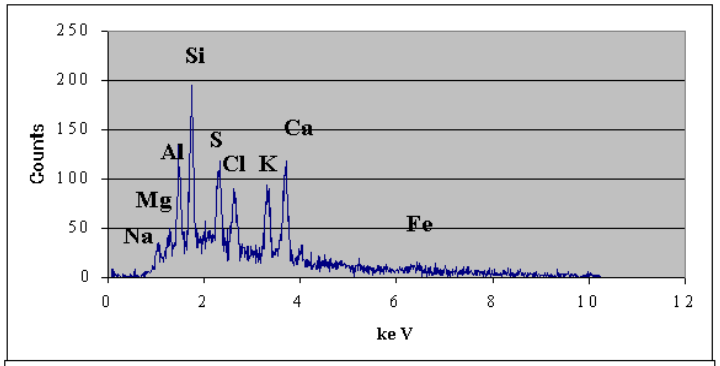


Figure 2a

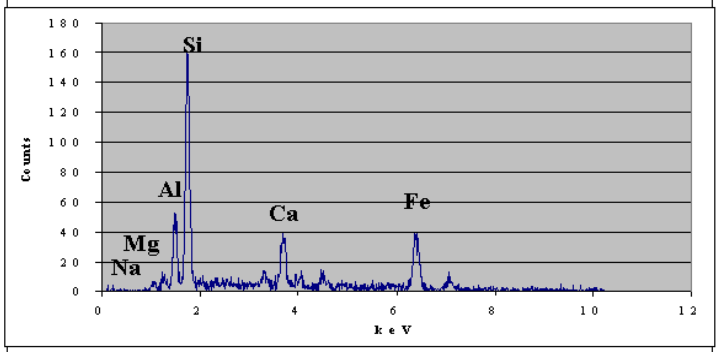


Figure 2b

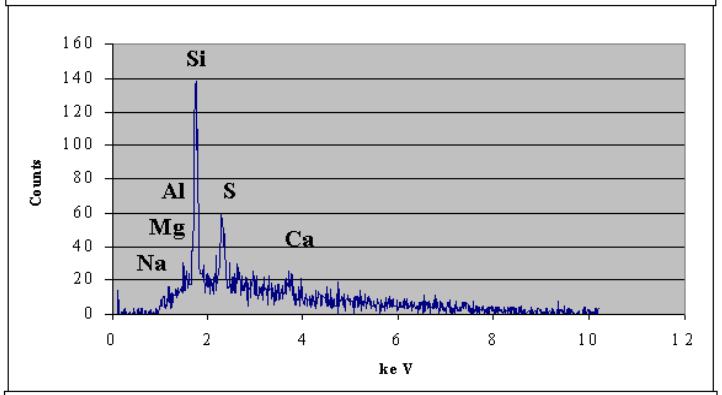


Figure 2c

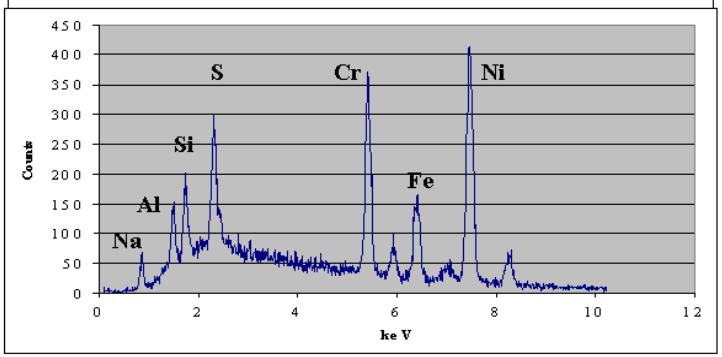


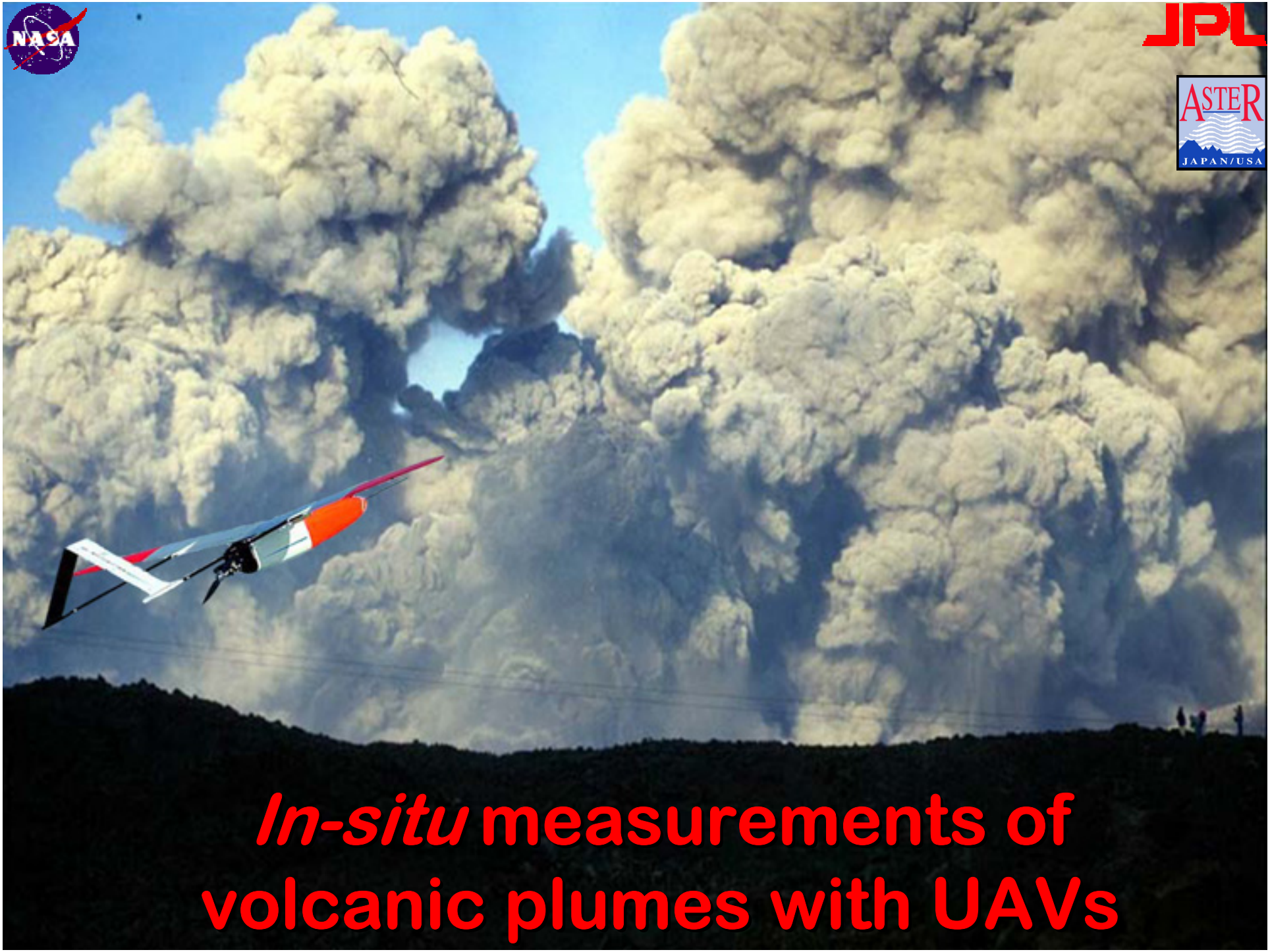
Figure 2d

Scanning Electron Microscope Results

Pieri *et al.*, *GRL*, 2002

Hekla Conclusions

- Despite initial assertions to the contrary (e.g., Rose et al) based on TIR remote sensing data, there is incontrovertible in-situ evidence (Grindle et al; Pieri et al.) that the NASA DC-8 encounter en-route volcanic ash.
- The hypothesis that the TIR ash signature was masked by ice coatings on ash grains was confirmed by analysis of simultaneous radar observations from Reykjavik airfield.
- Ash plume trajectory estimates from the London VAAC were in error because of lack of information on the ash injection altitude.
- Improved “split window” data/model iterative techniques are urgently needed, as are more comprehensive orbital multispectral TIR observations.
- High latitude volcanoes pose an especially severe observational and phenomenological issues (e.g., icing; infrequent polar orbiter data).

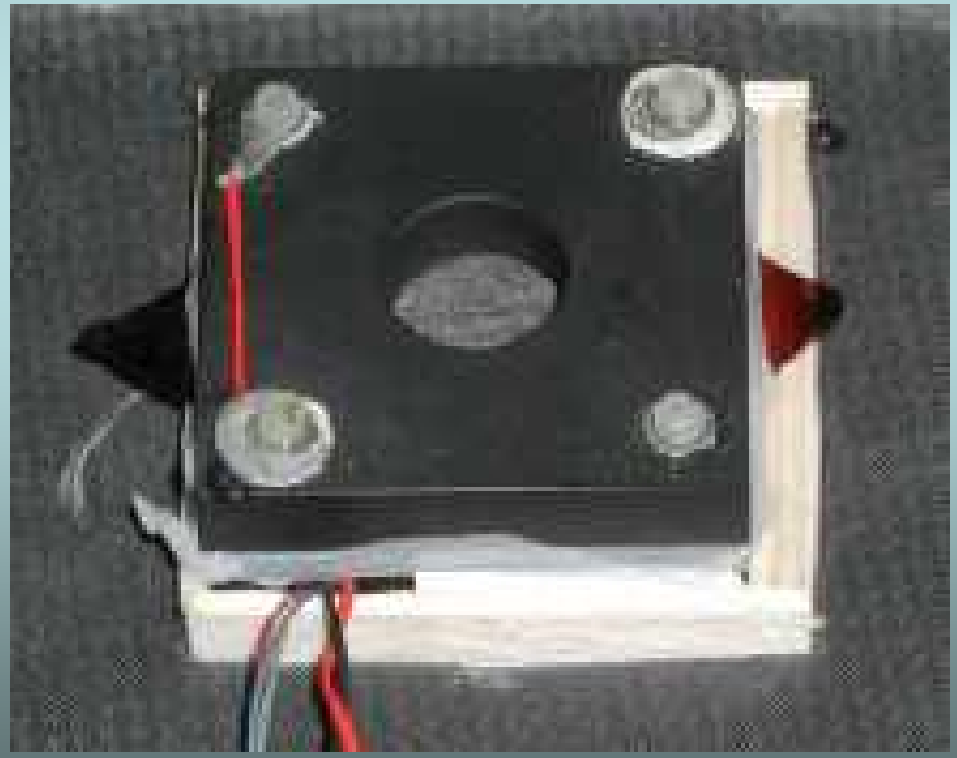

NASA
JPL
ASTER
JAPAN/USA
In-situ measurements of
volcanic plumes with UAVs

Coordinated approach for Volcanic ash and SO_2 plume observations

- Orbital—ASTER, MODIS, EO-1, others
- Airborne overflights—TIMS, MASTER, MIVIS, others
- Airborne *in-situ* calibration and validation
  - Robotic aircraft, balloons
  - *Critically important to validate remote sensing detection thresholds of number density and concentration*

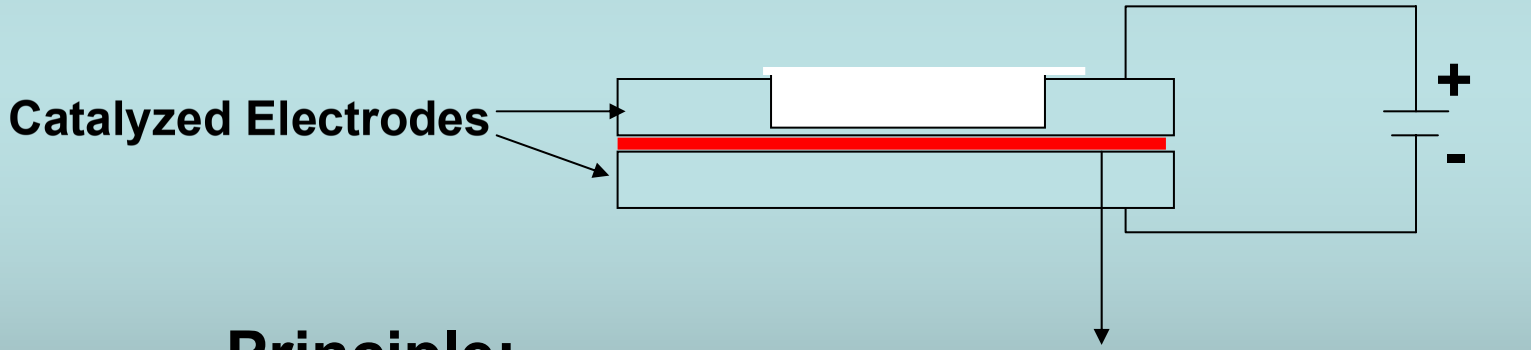
First Generation (Gen1) Electrochemical SO_2 sensor

- **Approximately 4cm across**



In-Situ SO_2 Measurements-- Principle of the Sensor

A schematic diagram of the sensor is shown below:

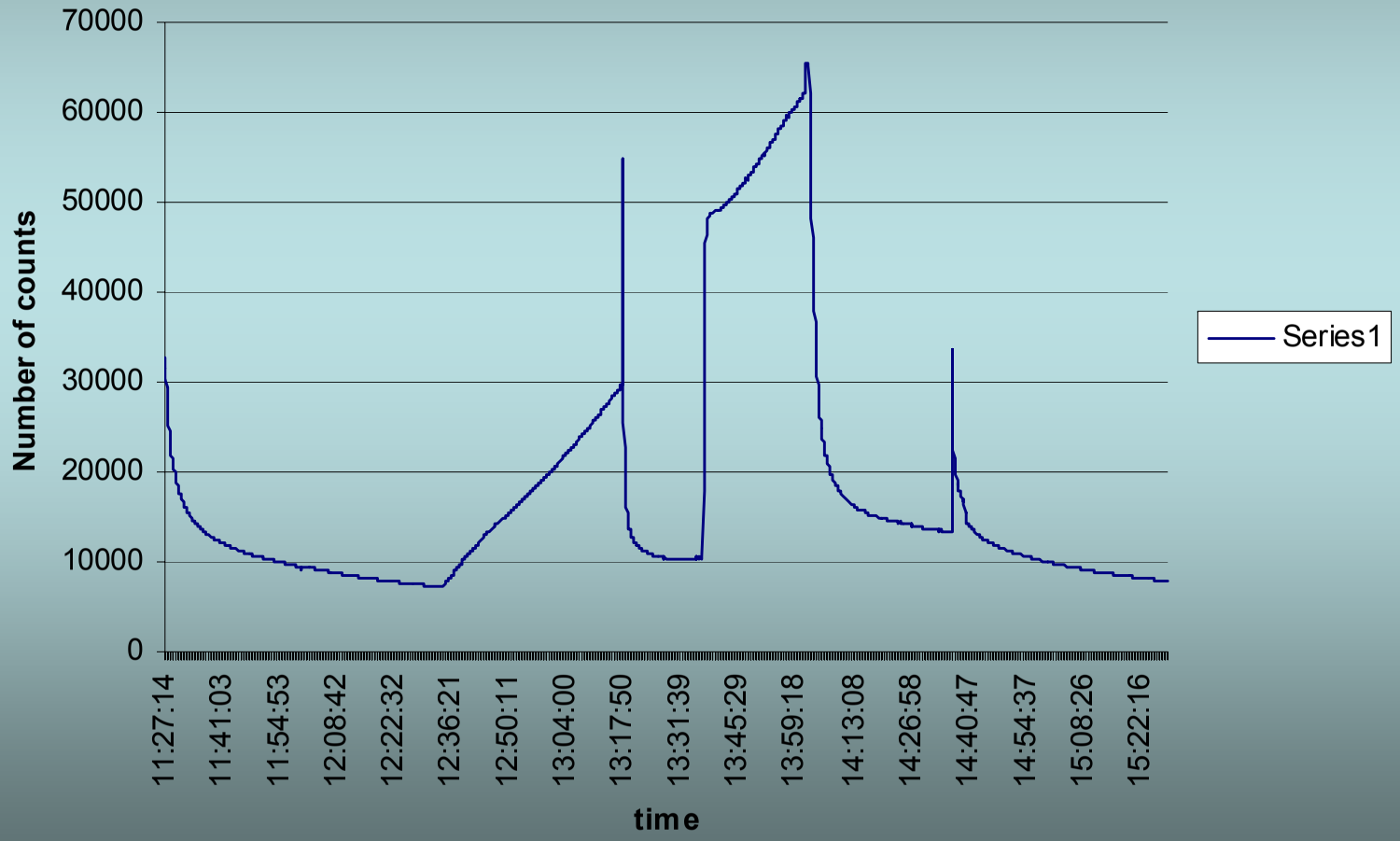


Principle:

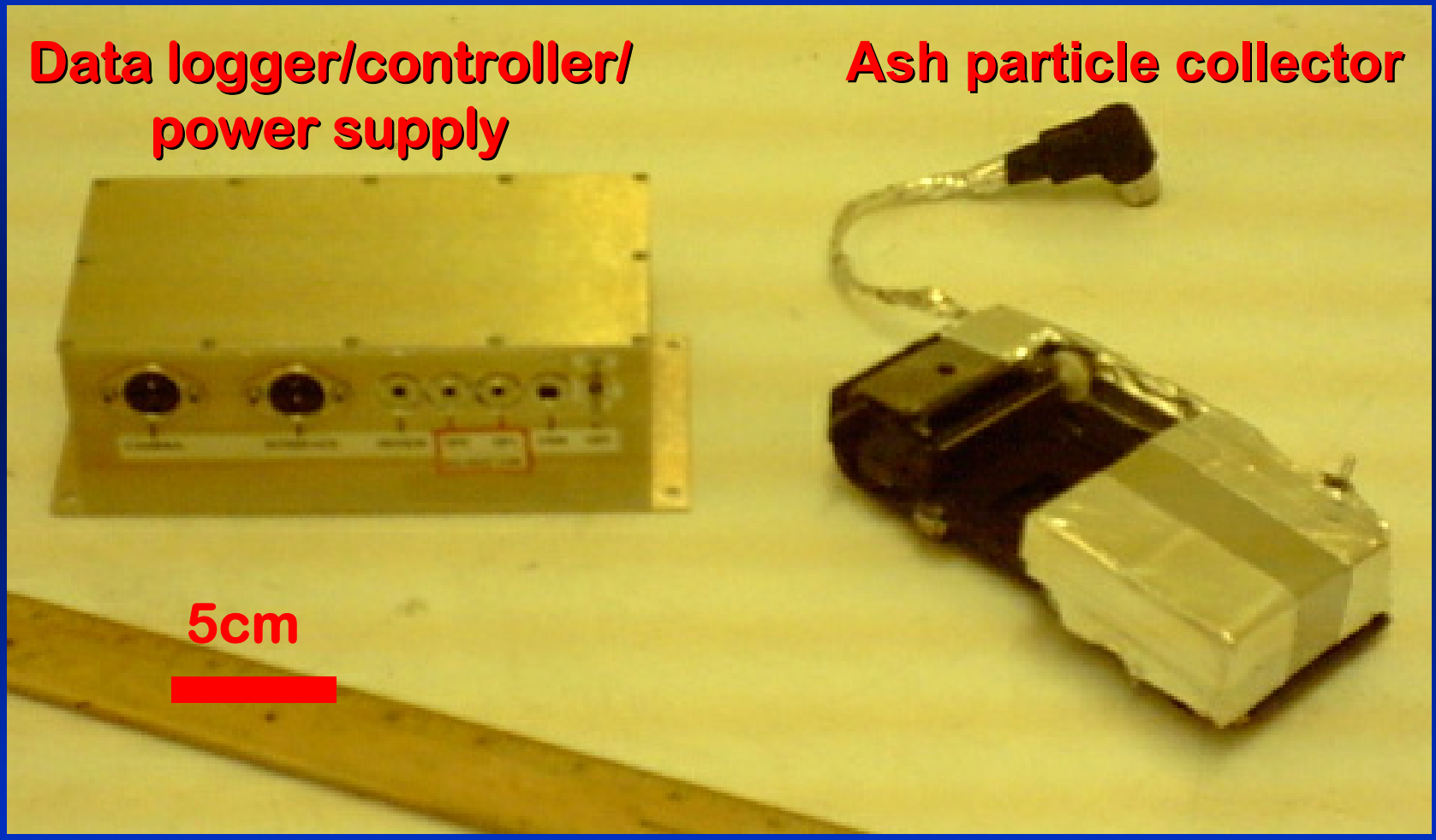
$$SO_2 + 2H_2O \longrightarrow SO_4^{2-} + 4H+ + 2e^-,$$
$$2H+ + 2e^- \longrightarrow H_2$$

In-Situ SO_2 Sensor— Transient Response Curve

04/07/03



UAVs for Volcanic Hazards



New Second
Generation
SO_2 Sensor
CTL GAS: SO2
Energizer
04.21.2005 18:48

Robotic Aircraft for *In-Situ* Cal/Val Measurements

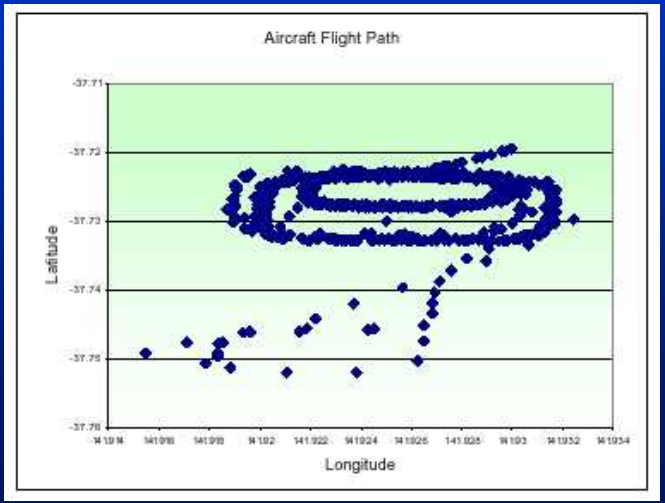
- Aerosonde Pty. Ltd. and Aerosonde North America
  - Robust small robotic aircraft
  - Supercharged engine for high altitude
  - 7kg payload for local flights
  - Capable of flying long over-water missions
  - Successfully flight tested Gen1 SO_2 sensor including special induction shroud
- University of Bologna
  - Short range (<10km) small robotic aircraft
  - 2kg payload
  - Successfully flight tested Gen1 SO_2 sensor

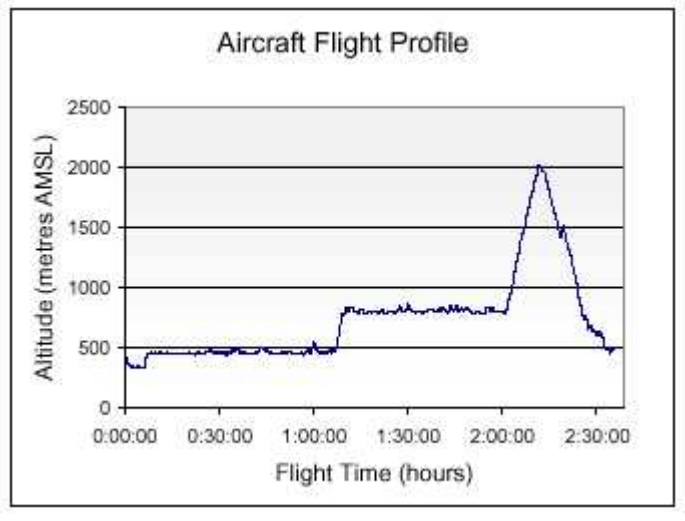
UAVs for Volcanic Hazards

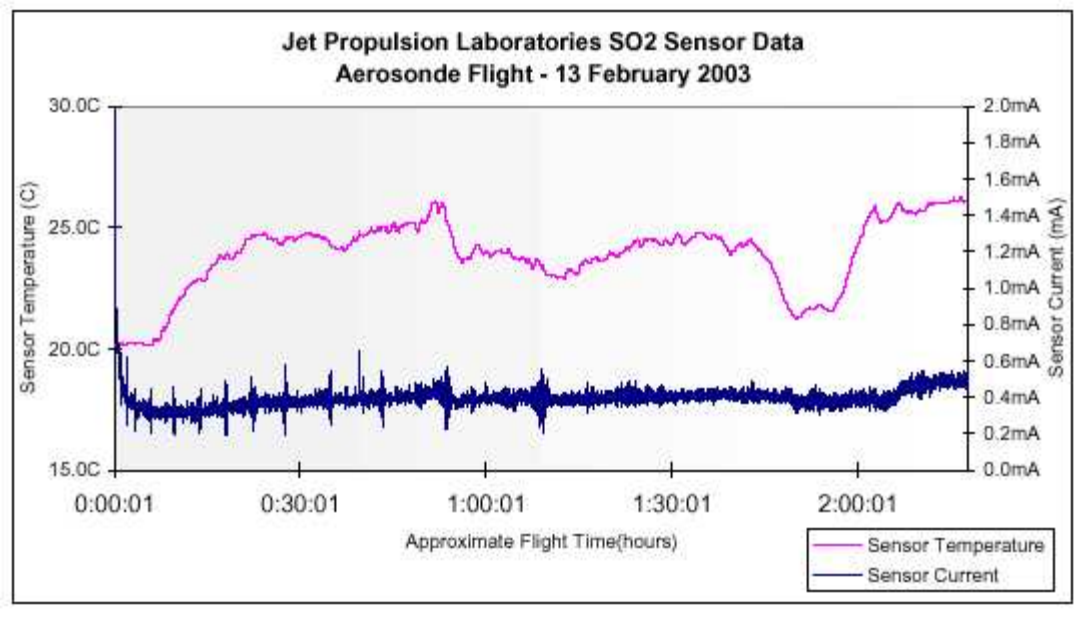
Aerosonde

UAVs for Volcanic Hazards

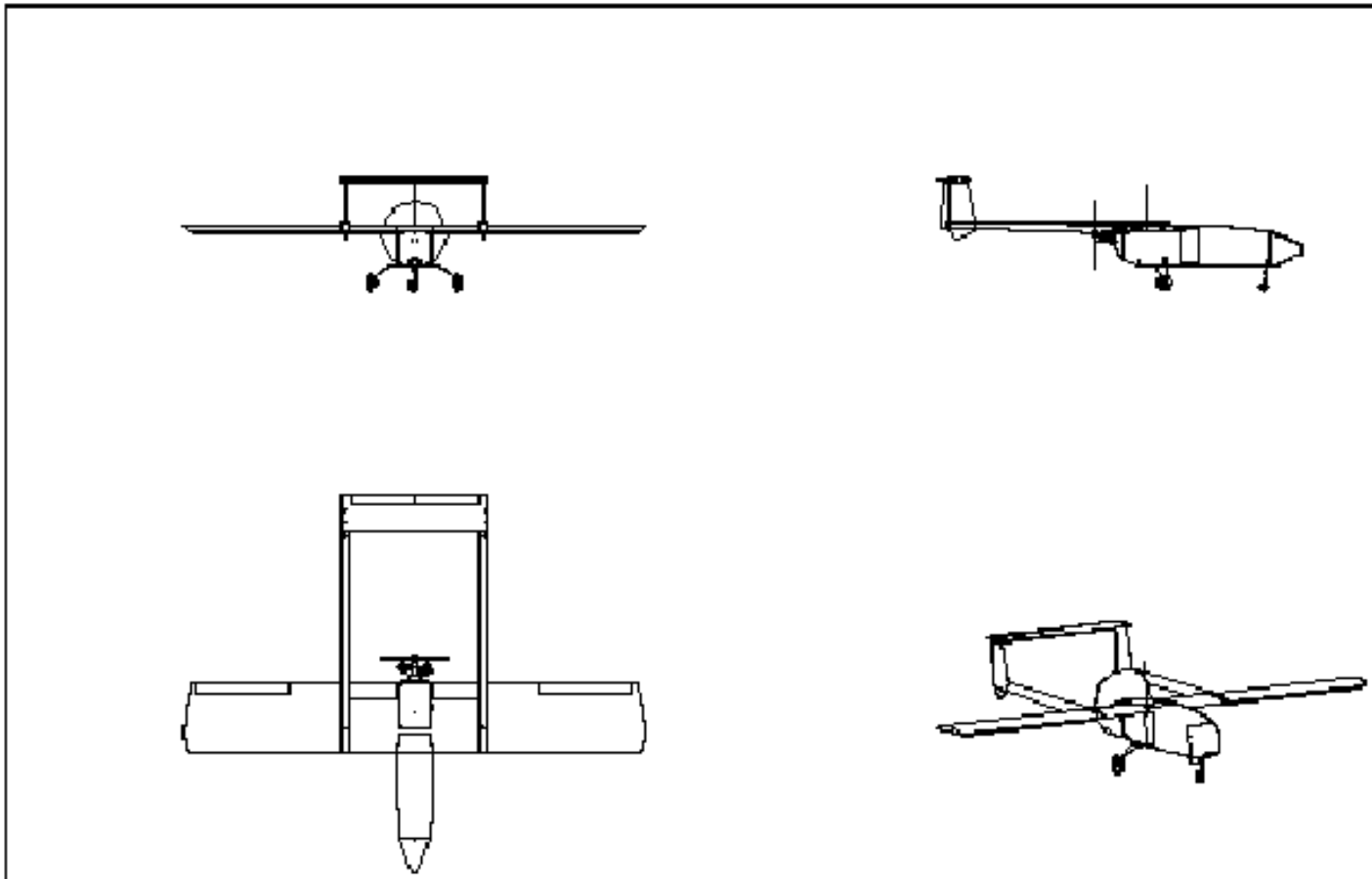
Aerosonde Flight Test







Unibo UAV

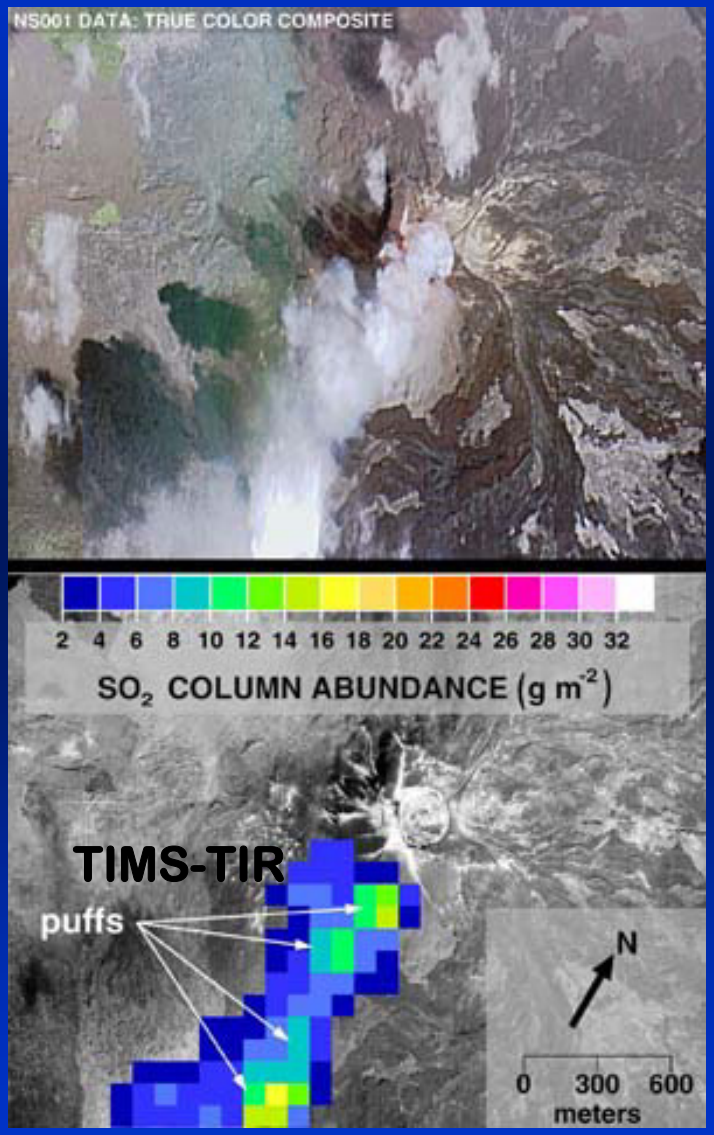


ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

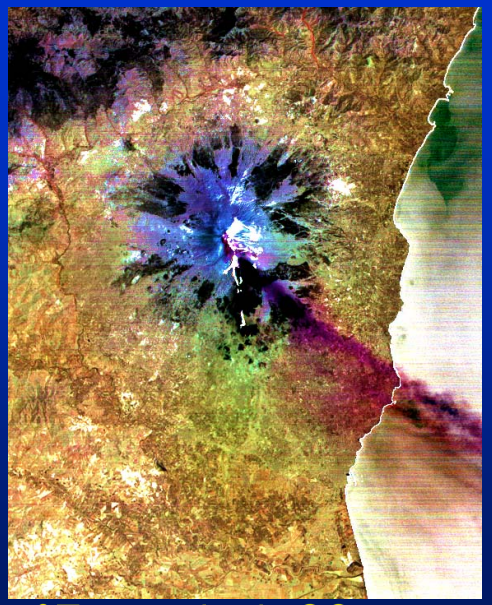
UAVs for Volcanic Hazards
ASTER
JAPAN/USA
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
Unibo UAV

UAVs for Volcanic Hazards

SO_2 Detection and Tracking

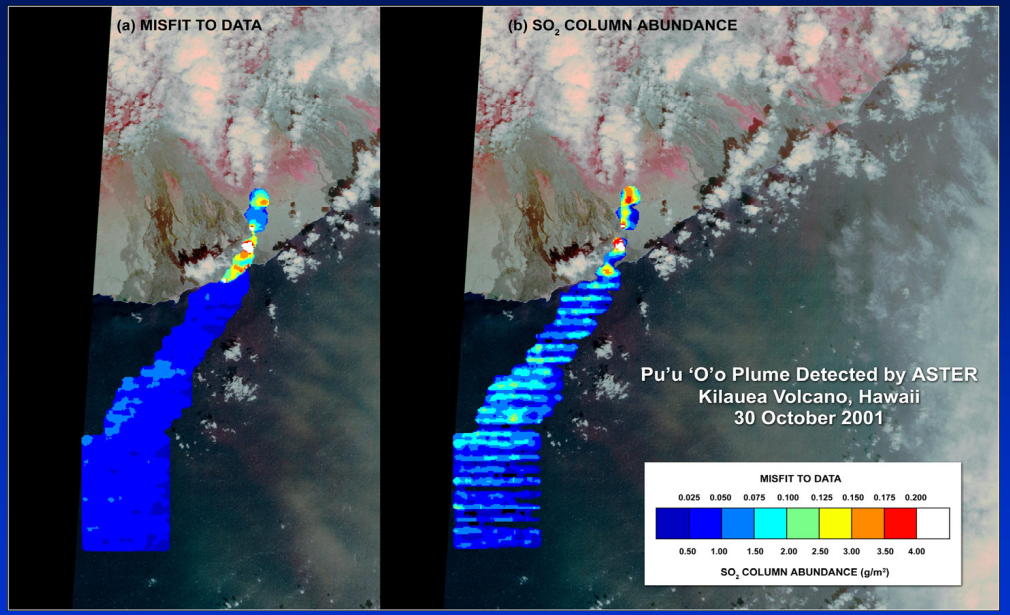

NS001 DATA: TRUE COLOR COMPOSITE
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
SO2 COLUMN ABUNDANCE (g m-2)
TIMS-TIR
puffs
N
0 300 600
meters

Courtesy Vince Realmuto, JPL

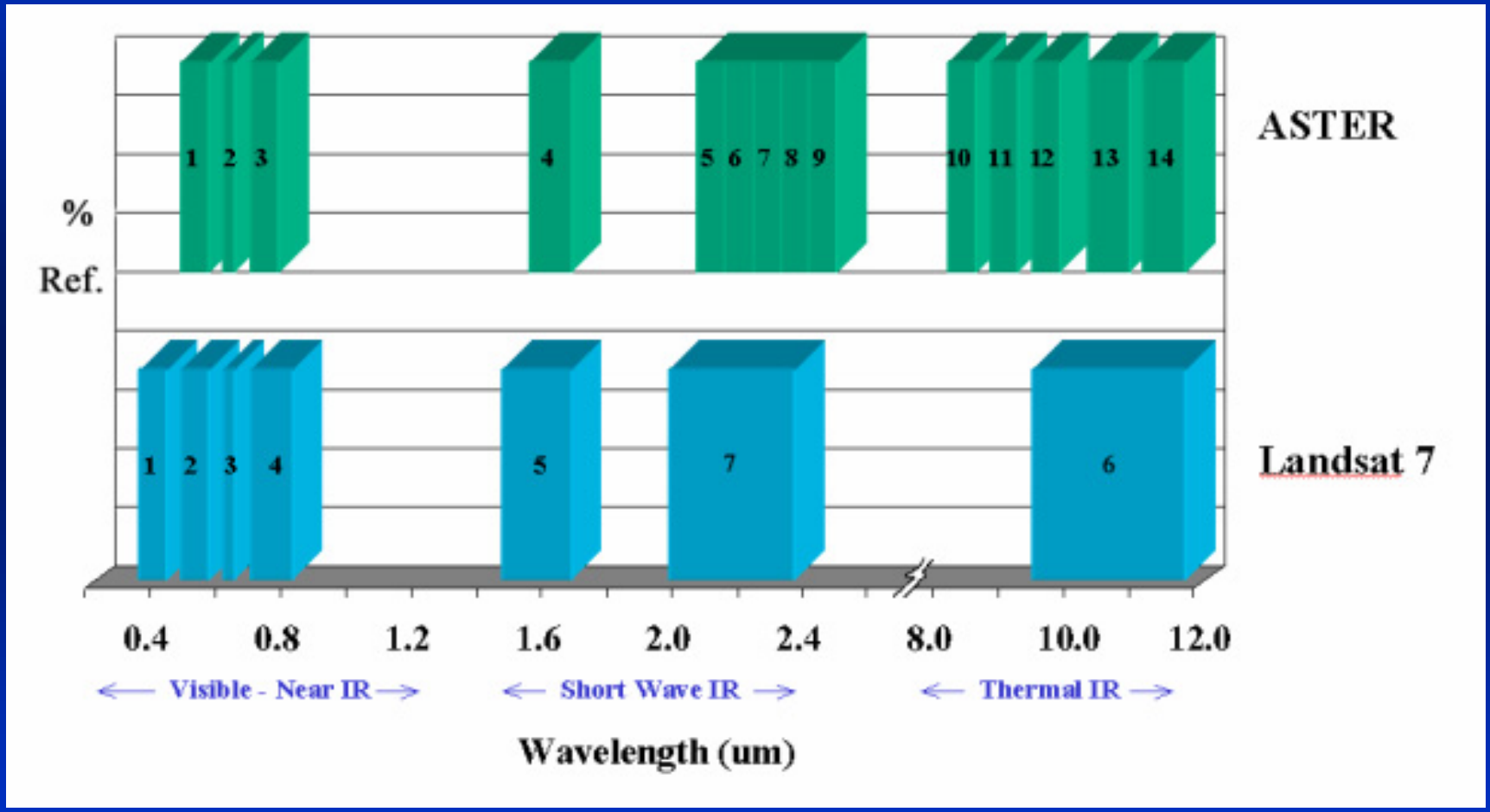


Airborne Detection from NASA C130 in over PuuOo Vent, Kilauea (left)

Orbital Detection of Tropospheric SO_2
ASTER over Hawaii (below) and Mt. Etna, Italy (above)


(a) MISFIT TO DATA
(b) SO2 COLUMN ABUNDANCE
Pu'u 'O'o Plume Detected by ASTER
Kilauea Volcano, Hawaii
30 October 2001
MISFIT TO DATA
0.025 0.050 0.075 0.100 0.125 0.150 0.175 0.200
0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00
SO2 COLUMN ABUNDANCE (g/m2)

ASTER vs. Landsat 7 Bands



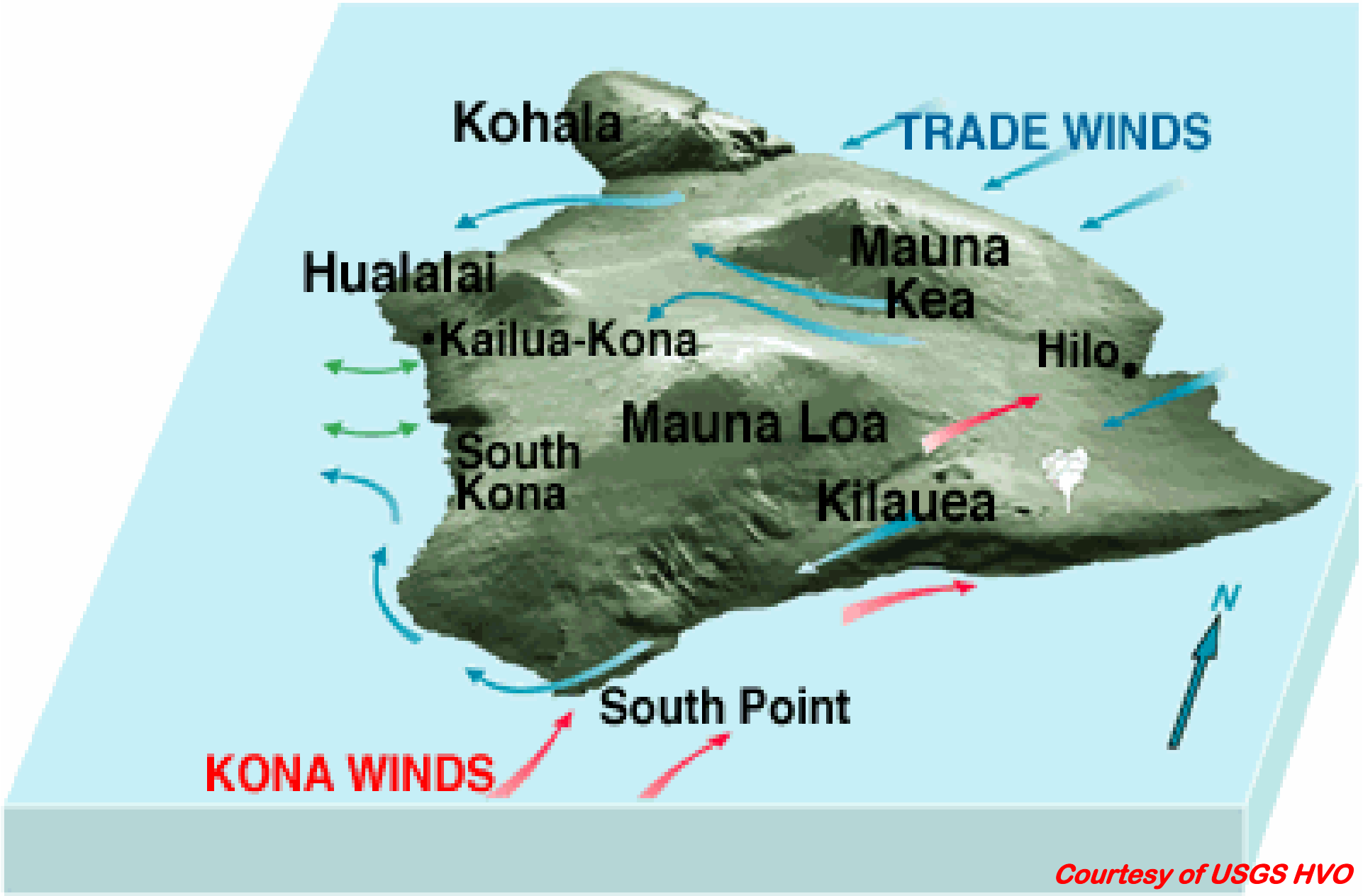
UAVs for Volcanic Hazards

5. Current Plans

- Hawaii—Ground and airborne, Spring/Summer ’05, SO_2 sampling at PuuOo Vent. (Mauna Loa 200X?)
- Stromboli Volcano & Mt. Etna—UniBo UAV, Summer/Fall ‘05. SO_2 and particle sampling.
- South Pacific—Aerosonde, ’05-’06?

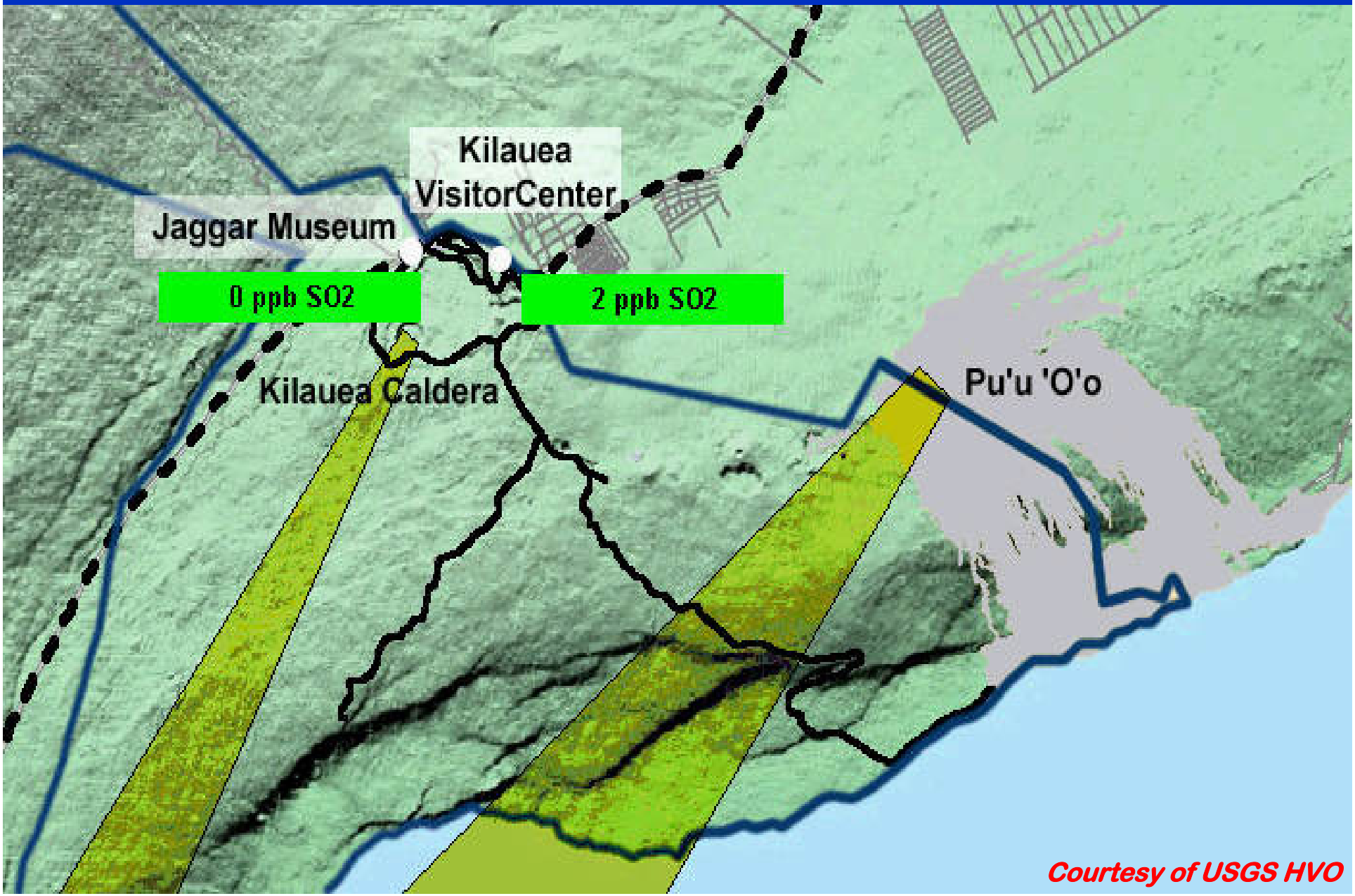
  White Island, NZ, SO_2 sampling

Wind Patterns--Hawaii



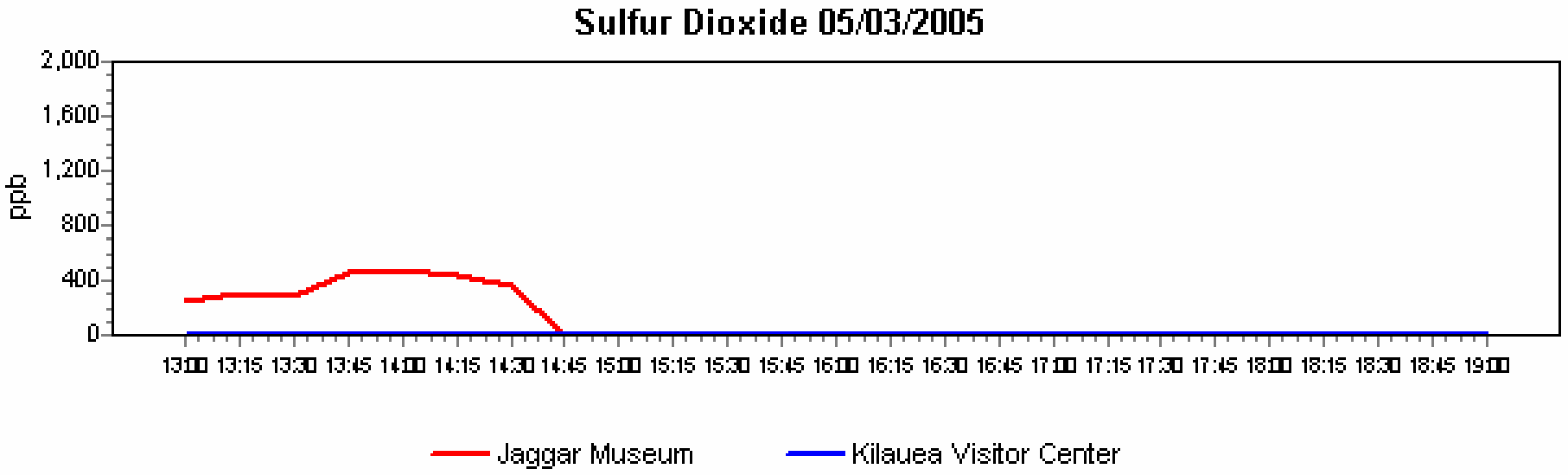
Courtesy of USGS HVO

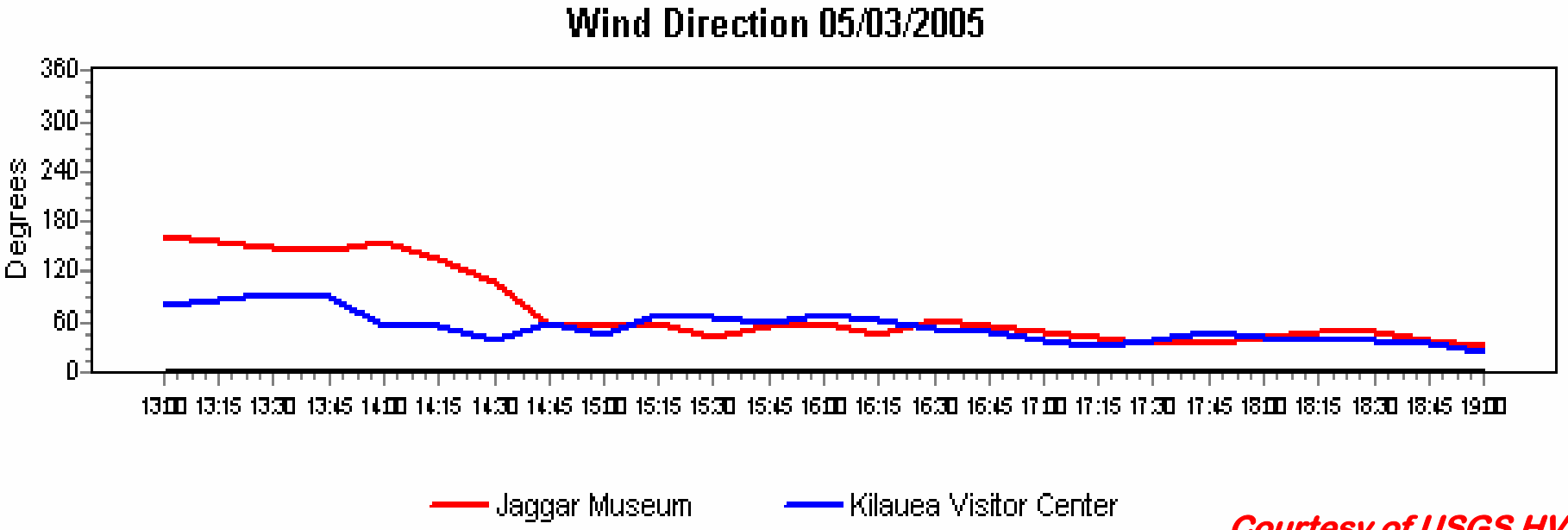
Kilauea Surface SO_2



Courtesy of USGS HVO

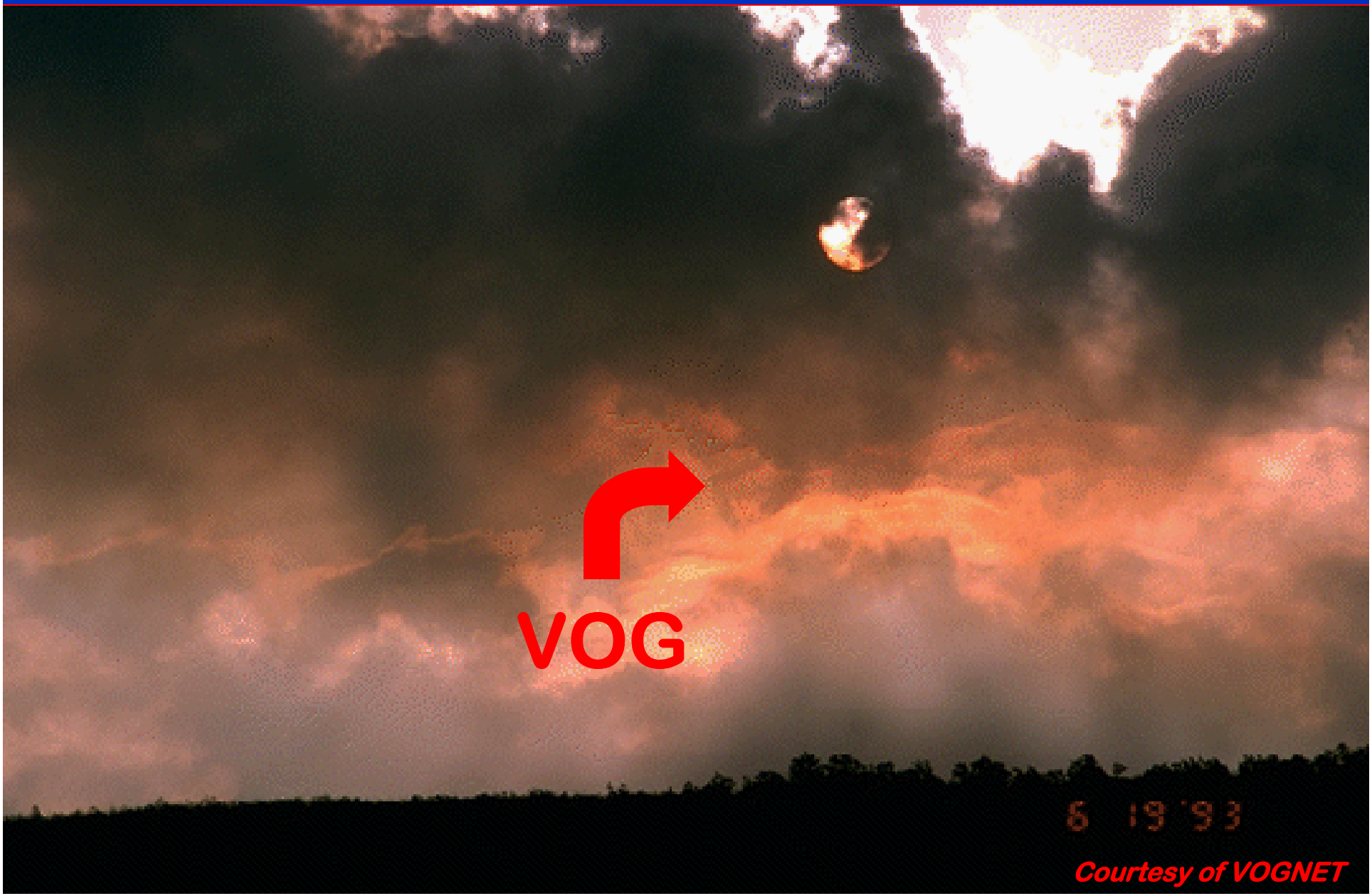
Kilauea Surface SO_2





Courtesy of USGS HVO

This Photo Not Provided by the Big Island Chamber of Commerce



Major Volcanoes of Italy

USGS

Topinka, USGS/CVO, 1998; basemap modified from: CIA map, 1997; volcanoes from Simkin & Siebert, 1994

Stromboli Volcano, Sicily

Stromboli Volcano, Sicily

Courtesy of stromboliguide.it

White Island, New Zealand

Uninhabited, 2x2.4km,
summit at 321mASL

Courtesy of Smithsonian

6. Conclusions and Issues

- UAV missions can obtain critical data that are otherwise inaccessible
- Orbital observations cannot be effectively conducted without comprehensive airborne and *in-situ* support missions for sensor and algorithm calibration and validation
- UAV accessibility for rapid deployments are still an issue (e.g., recent Mt. St. Helens experience).
- The high costs of UAV deployments are a severe limitation for individual PIs (e.g., Predator, Aerosonde).
- Airspace clearance is still a big issue.

Related Summary Bibliography

Pieri, D, Abrams M, 2005, ASTER Observations of thermal precursors to the April 2003 eruption of Chikurachki Volcano, Kurile Islands, Russia, accepted for publication, *Remote Sensing of Environment*.

Pieri D, Abrams M, 2004, ASTER watches the world's volcanoes: a new paradigm for volcanological observations from orbit, *Journal or Volcanology and Geothermal Research 135* (1-2): 13-28.

Lombardo V, Buongiorno MF, Pieri D, et al., 2004, Differences in Landsat TM derived lava flow thermal structures during summit and flank eruption at Mount Etna, *Journal of Volcanology and Geothermal Research 134* (1-2): 15-34.

Simpson JJ, Hufford GL, Servranckx R, Berg, J., Pieri, D. et al., 2003, Airborne Asian dust: case study of long-range transport and implications for the detection of volcanic ash *Weather and Forecasting 18 (2)*: 121-141.

Pieri D, Ma C, Simpson JJ, et al. 2002, Analyses of in-situ airborne volcanic ash from the February 2000 eruption of Hekla Volcano, Iceland, *Geophysical Research Letters 29 (16)*: Art. No. 1772.

Simpson JJ, Hufford GL, Pieri D, et al., 2002, The February 2001 eruption of Mount Cleveland, Alaska: Case study of an aviation hazard, *Weather and Forecasting 17 (4)*: 691-704.

Simpson JJ, Hufford GL, Pieri D, et al., 2001, Failures in detecting volcanic ash from a satellite-based technique – Response, *Remote Sensing of Environment 78 (3)*: 347-357.

Simpson JJ, Hufford G, Pieri D, et al., 2000, Failures in detecting volcanic ash from satellite-based technique, *Remote Sensing of Environment 72 (2)*: 191-217.

Hufford GL, Salinas LJ, Simpson JJ, Barske, EG, Pieri, D., 2000, Operational implications of airborne volcanic ash Bull. Am. Met. Soc. 81 (4): 745-755.

7. Summary of ASTER Volcanology Data Archive and Analysis System (VDAAS)

- On-line systematic access to retrospective ASTER images and future ASTER data acquisition footprints and XML data.
- Baseline data for precursor comparisons--L1A, L1B, and L2+
- Dedicated 5TByte+ server--web-accessible to the public:
  - –Meta-data from the LPDAAC FTP site → shape files
  - –Displays multiple layers of data; queries for specific information.
  - –This algorithm will be expanded/reconfigured to include downloadable images and a limited suite of derived data products.
- Follow-on: add massively parallel processors for data analyses

TEAM

PI: Dave Pieri, JPL—Project management; thermal radiance, aerosol, and lava flows; thermal algorithms (Science Team Member)

Co-I/Deputy PI: Michael Abrams, JPL—Project management; geologic evaluations of eruption parameters (w/Pieri) (Science Team Leader)

Co-I: Vince Realmuto, JPL—SO_2 algorithms, data analysis; time-series process simulations (Team Member)

Co-I: Mike Ramsey, University of Pittsburgh— ArcIMS web-browser conversion to VDAAS (Team Member.

Co-I: Ashley Davies, JPL—Two-band thermal emissions models/algorithms (Team Associate).

Co-I: Alan Gillespie, University of Washington—Temperature-emissivity separation issues, variable emissivity studies and algorithms; volcanic lake study (Team Member).

Co-I: Tim Gubbels, Science Systems and Applications, Inc--External interfaces (e.g., EOSDIS, EOSDIS Data Pools, the LPDAAC); data and metadata transfer protocols; Central America volcano hazards; MODIS liaison (Team Associate)

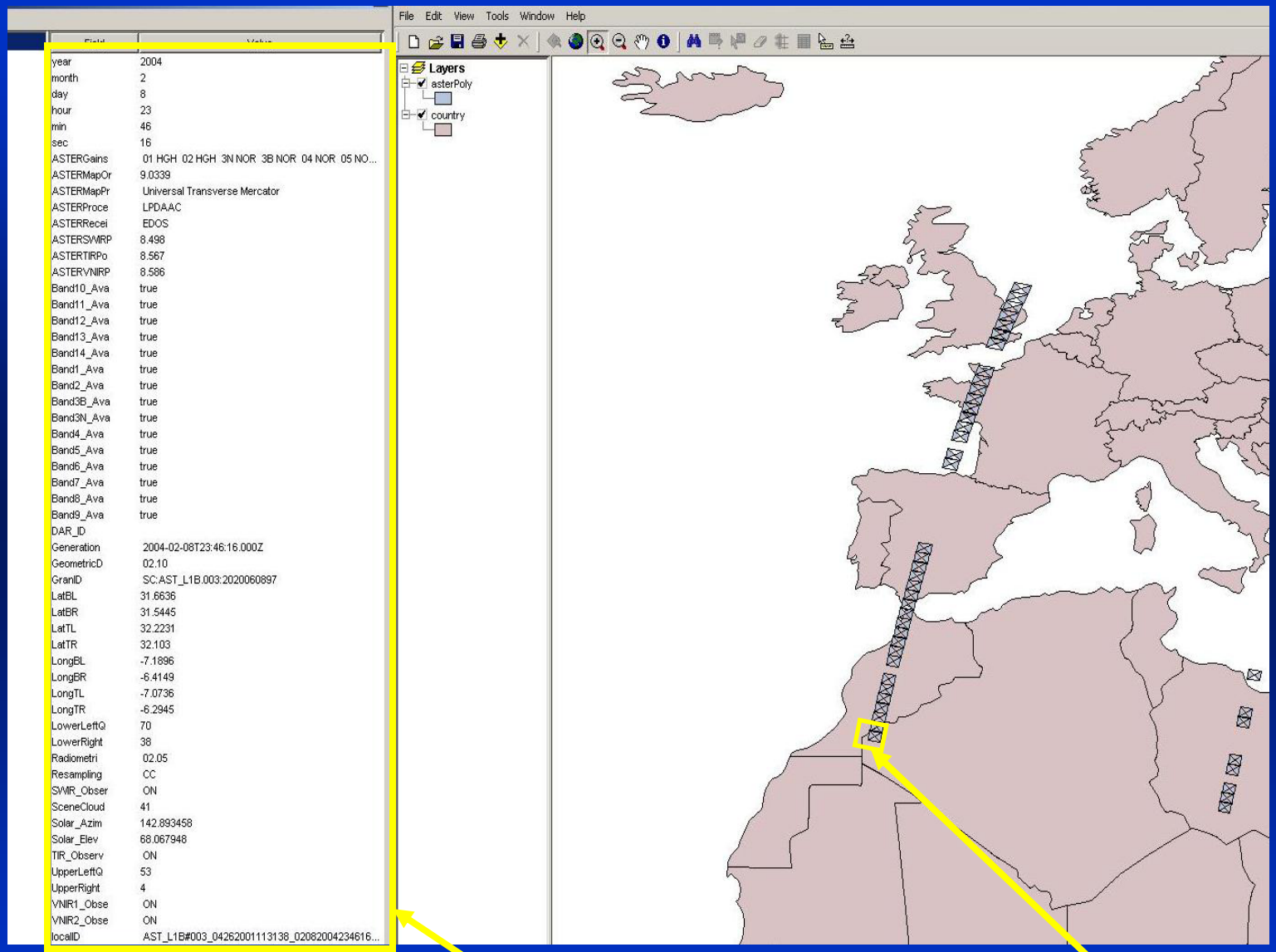
GOAL: Web Accessible Systematic Characterization and Cataloging of Volcanoes Worldwide

- Systematic characterization of over 1000 volcanoes observed by ASTER

- Comprehensive self-consistent terrestrial global remote-sensing volcano survey and monitoring program

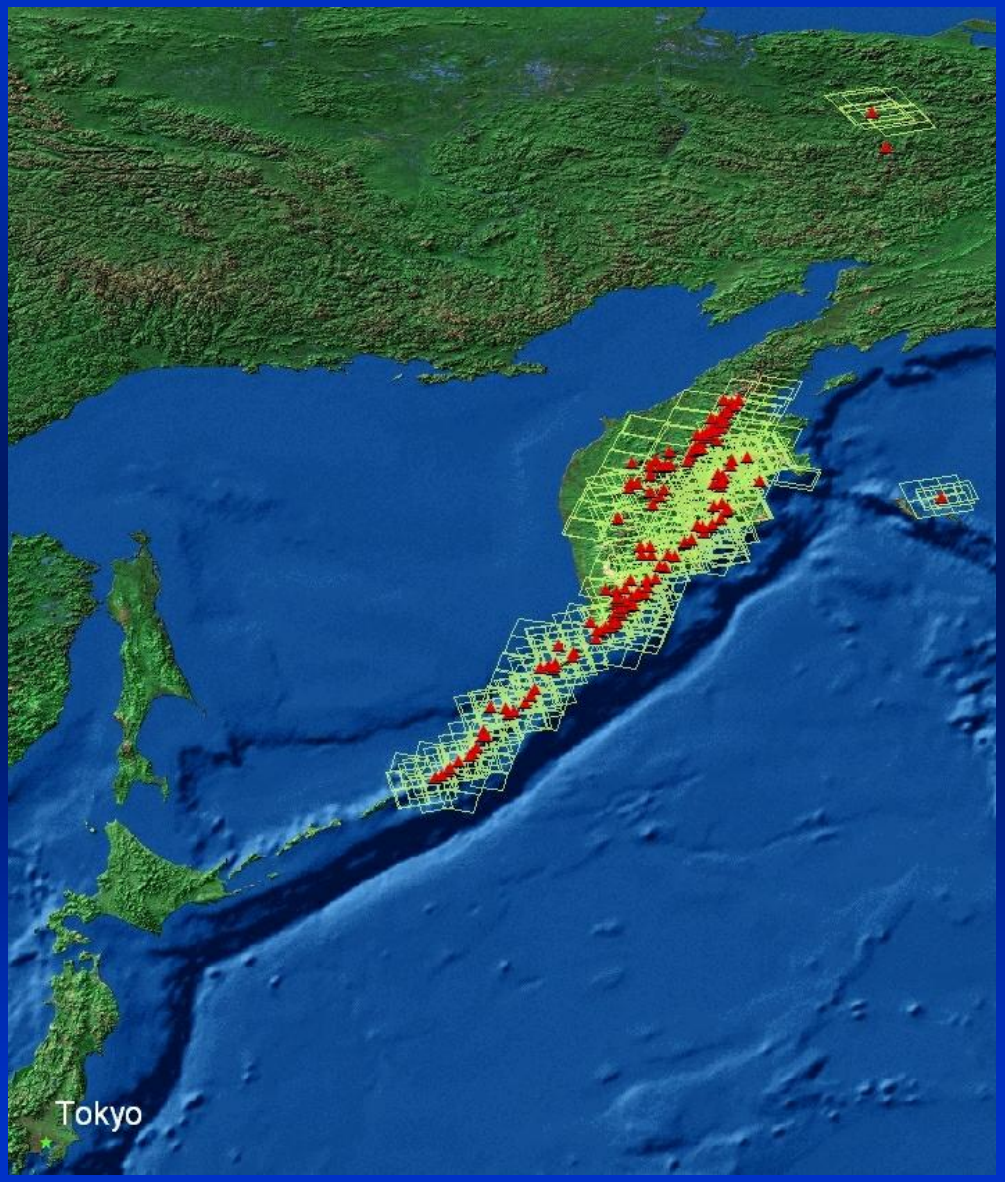
- 10^1-10^2m/pixel spatial scale; 0.4-12.5μm spectral range

VDAAS Proto-GUI



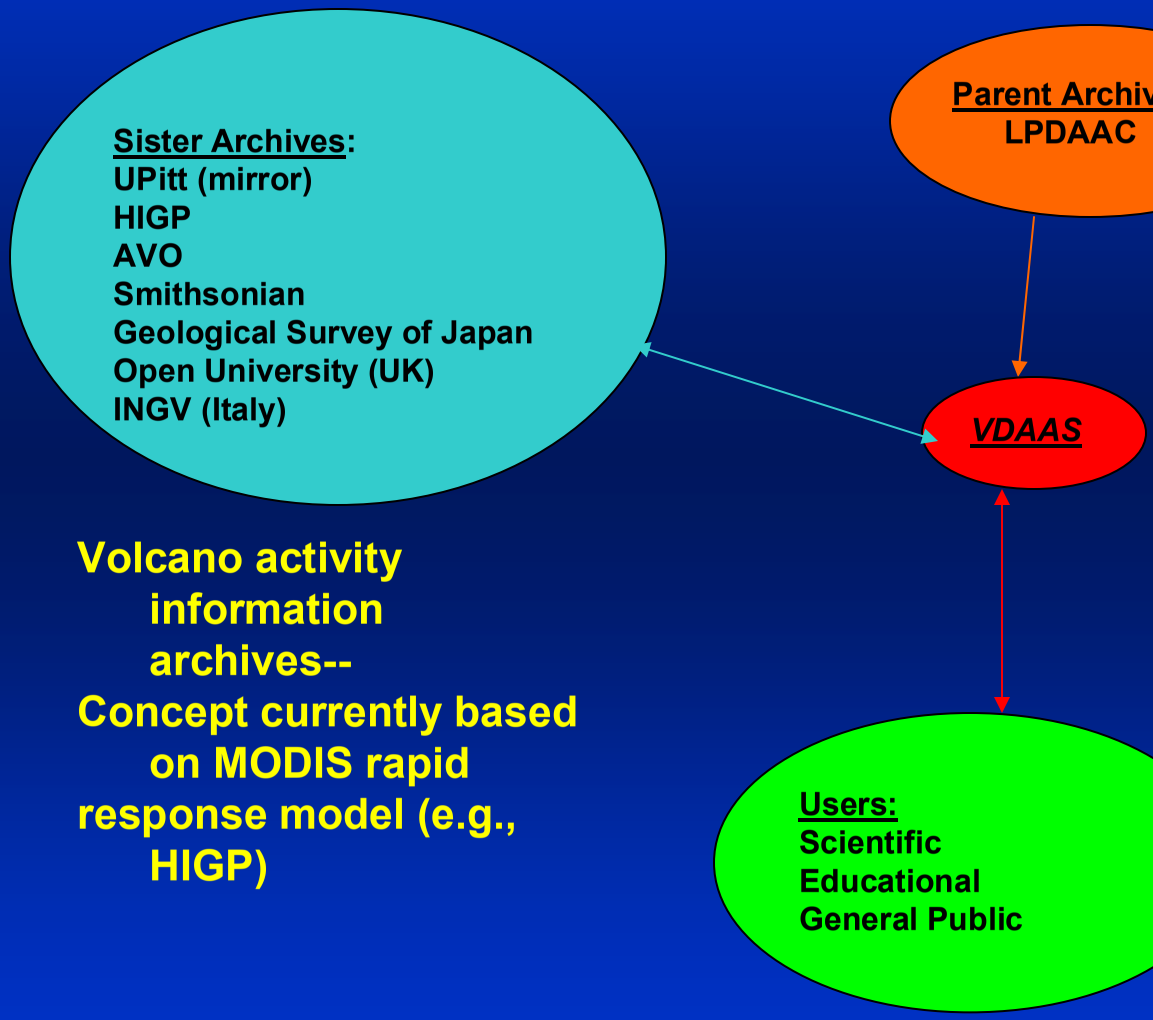
Able to extract meta-data from individual ASTER polygon

ASTER Data for Kamchatka: GUI Example



- Kamchatka-Kurile Arc shown in GUI.
- Shows ASTER L1B + scene/volcano locations overlain as GIS layers.
- Scene polygons are "clickable" and contain meta-data information.
- The background image is a MODIS+DEM perspective map super- imposed on a sea-surface height DEM.
- GUI will then be the gateway for researchers:
  - volcanology
  - climate research,
  - hazards R&D, etc.

VDAAS Scheme



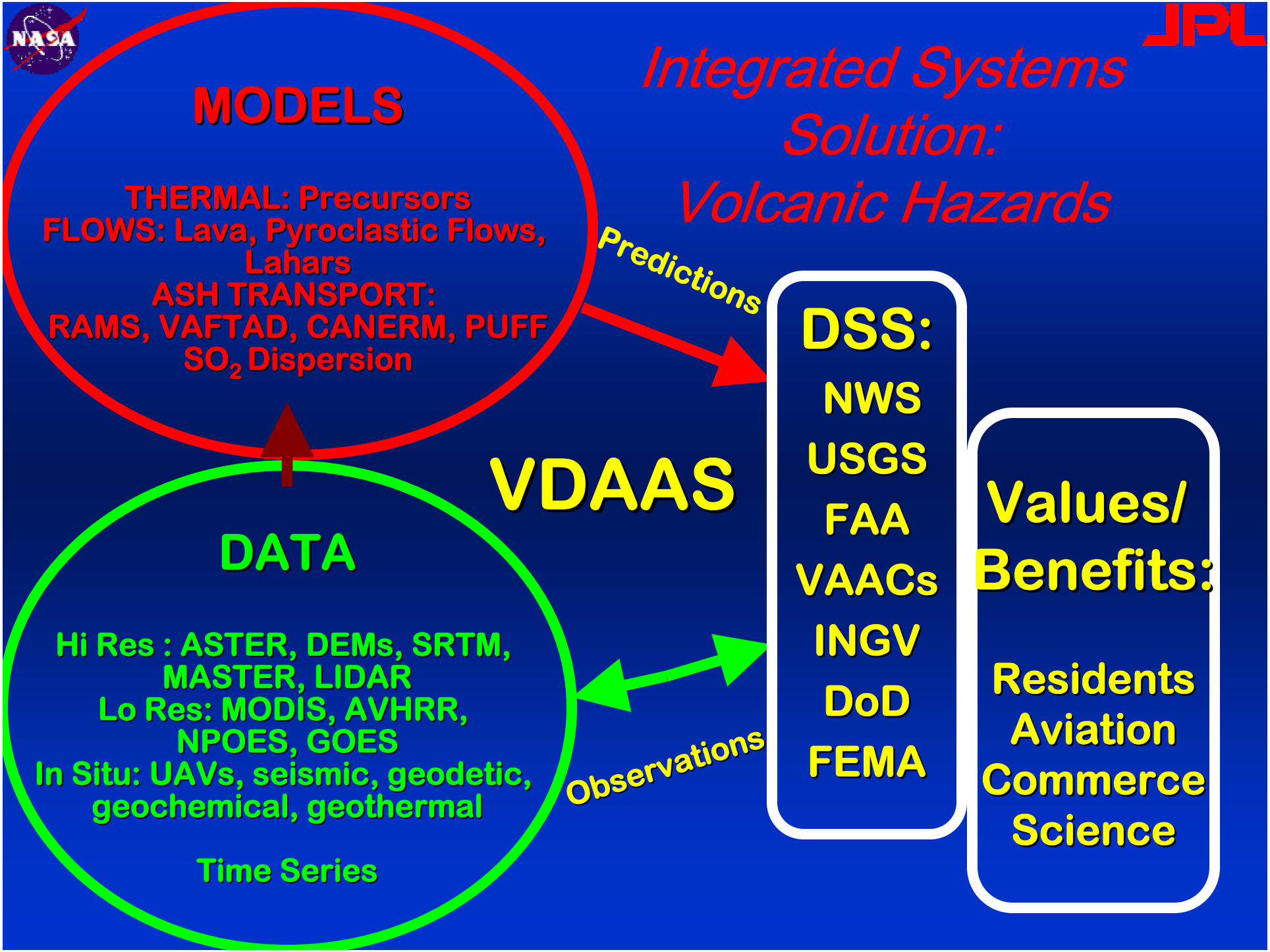
Granule information in XML.
Browse images & VNIR-SWR-TIR data
Level 2 products (e.g. corrected surface temperature)

Volcano activity information archives--
Concept currently based on MODIS rapid response model (e.g., HIGP)

Local ASTER volcanolgy archive
Query data through web browser
Data served on Java program server (Tomcat) and HTML server (Apache)
Data Products for scientific analysis
Derived Products (SO_2 abundance, Ash Encounter Probabilities, volcano DEMs, etc.)

VDAAS Summary

- Emphasis on analyses of geo-located multispectral volcanological time-series at high spatial resolution
- Rationalize and provide easy web-based access to ASTER data for volcanoes
- Provide convenient access to relevant volcanological algorithms
- Interact with other archives (e.g., AVO, UofH, Smithsonian)
- Development is being funded by NASA Solid Earth Science
- Has relevance to NASA Hazards Applications in the CAN environment as part of decision support system architecture
  - High spatial resolution data for meso-scale hazard evaluations (e.g., boundary layer transport of volcanic ash near airports; other hazards)
  - For instance, interface with RAMS model
  - Interface with World Winds GUI
  - Ingestion of MASTER and UAV data


Integrated Systems Solution: Volcanic Hazards
MODELS
THERMAL: Precursors
FLOWS: Lava, Pyroclastic Flows, Lahars
ASH TRANSPORT:
RAMS, VAFTAD, CANERM, PUFF
SO_2 Dispersion
Predictions
DATA
Hi Res : ASTER, DEMs, SRTM, MASTER, LIDAR
Lo Res: MODIS, AVHRR, NPOES, GOES
In Situ: UAVs, seismic, geodetic, geochemical, geothermal
Time Series
Observations
VDAAS
DSS:
NWS
USGS
FAA
VAACs
INGV
DoD
FEMA
Values/ Benefits:
Residents
Aviation
Commerce
Science